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Applications of Pitch and Intensity Measurements of Connected Speech

JOSEPH TIFFIN, *University of Iowa*
(Received January 22, 1934)

EVERYONE interested in acoustics is aware of the growing consciousness of speech and voice. It may not be so apparent, especially to those in commercial and industrial work, that this development is causing some important changes in academic curricula. Courses in speech correction, a relatively new offering, are now given by 76 American colleges and universities. Courses in phonetics which deal with the physics and physiology of voice production are becoming very numerous. In some institutions there is a compulsory requirement that all incoming Freshmen enroll in a course in speech training.

These courses are not concerned with teaching declamation or oratory or interpretative reading. They do not spend time in developing vocal gymnastics which may be used only once or twice a year in boring a church congregation or literary society. Rather, these courses attempt to teach the student to develop his ordinary speech and speaking voice so that the vocal expression which he uses daily will be adequate, fluent, not unpleasant to his listeners, and devoid of speech defects, such as stuttering and lisping. The objectives of the new speech training are thus well defined. It is another matter to devise pedagogical methods which will actually achieve these ends. It is our belief that training in speech, as in any other skill, is effective in proportion as it is specific and to the point, rather than haphazard and random. But training cannot be made specific until it is known what physical, physiological and psychological factors characterize a voice which is uniformly judged to be pleasant, effective, and, to put it plainly, "easy to listen to." Textbooks of speech and voice do not supply the needed data. The disagreement among various authors of speech texts, even upon the most vital points, is convincing proof that their subjective methods of speech analysis have not been adequate. The physical data on speech coming from analyses of telephone and radio engineers, although extremely valuable in many ways, do not suffice because they present a composite description of speech in general. They tell us the range of intensity used in ordinary speech, but they do not answer the question: How do good and poor speakers differ in range or in consecutive variations of intensity? They tell us what range of frequencies must be used if speech is to be transmitted intelligibly, but they do not reveal how an effective and interesting speaker makes skillful use of this range.

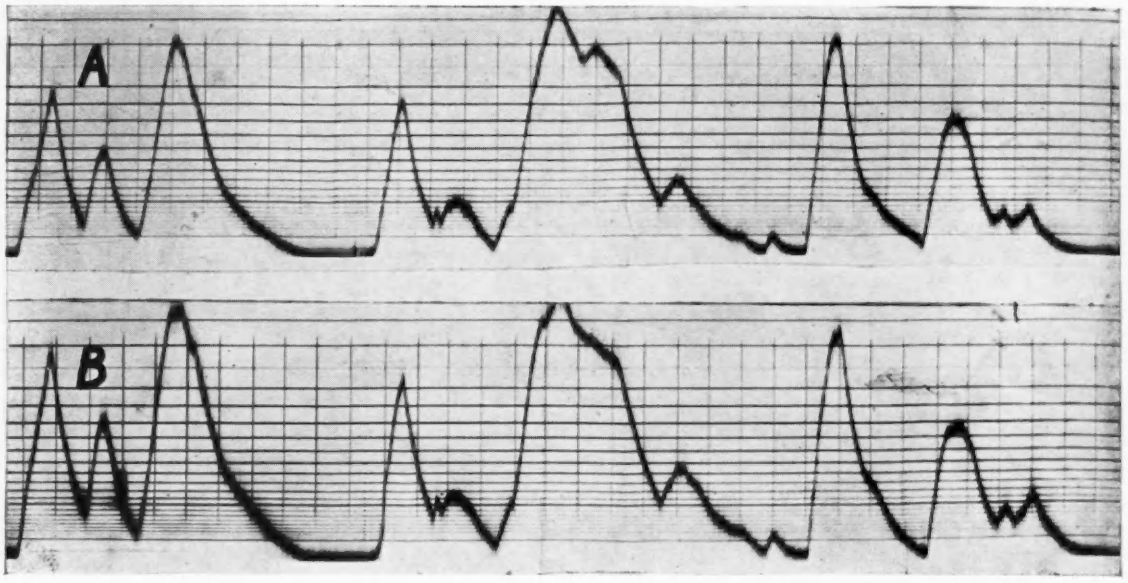

FIG. 1. Curves of consecutive speech taken on the high speed output level recorder.

Our researches in speech and voice at the University of Iowa are proceeding from a new point of view and with a changed emphasis. The aim of these researches is to enumerate and describe objectively the physical factors which make up pleasing and effective speech and voice. Such studies must deal eventually with every aspect of the sound wave, but the factors of pitch and intensity, which are relatively easy to record, have been particularly stressed. These studies may be considered as a phase of experimental esthetics, different from many studies in esthetics, however, in the important respect that the results may be put to immediate practical use in teaching.

A continuous record of the intensity level in consecutive speech is obtained by means of a high speed output level recorder.[1] Fig. 1A shows a reproduction of a film taken on this apparatus. The speech is picked up by means of a condenser transmitter and is amplified. The output of this amplifier is rectified, filtered, and sent into a Westinghouse supersensitive oscillograph element, which serves as an output level recorder. The sensitized paper is drawn by the recording element at the rate of 10 cm per sec. The vertical lines indicate time in tenths of a second, and the horizontal lines are separated by increments of one decibel. These lines are photographically ruled on the film, when the record is taken, by means of a continuously burning light and perforated shield. The element is properly damped to deliver square-topped waves when an instantaneous potential is applied at its terminals. The entire system has an approximately flat characteristic from 100 to 4000 cycles. The most serious objection to this apparatus is that the response is linear with voltage and accordingly it gives a range of only about 25 decibels on a film three inches in width.[2] Fortunately, the range of syllabic power, even in very emphatic speech, seldom exceeds this amount unless the speaker makes a deliberate attempt to use a very wide range.

A frequent variation in this procedure is to record the original speech upon an aluminum disk phonograph record and later photograph the intensity variations from the play-back of the recording. This offers several advantages because the performance may be heard after the physical records have been obtained. When this procedure was first used, it was thought that the cutter might introduce significant distortions in the

[1] J. Tiffin, *Phonophotographic apparatus*, University of Iowa Studies in Psychology of Music **1**, 118–133 (1932).

[2] Descriptions of several circuits have been published recently which record logarithmically. A recorder of this type is obviously more suitable for our work and is being adopted at present.

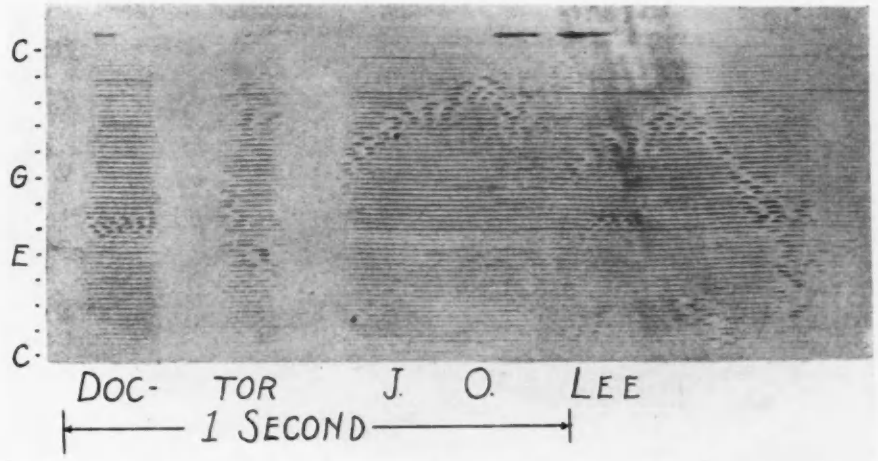

FIG. 2. Strobophotographic record of the words "Dr. J. O. Lee" as taken from consecutive speech.

record. Fig. 1 shows that these distortions are negligible. Curve A shows an intensity record obtained directly from a person speaking into the microphone. As curve A was photographed, a phonograph record of the speech was made. Curve B shows the intensity record photographed at a later time from this phonograph record. While curves A and B are not identical, they are similar enough to justify the use of this technique, and a thorough calibration of the cutter and play-back system probably would not alter this conclusion.

The pitch, or melody curve, in connected speech is obtained by either of two techniques, depending upon the degree of accuracy desired. In either case it is assumed that the pitch of a sound is determined by the frequency of repetition of the gross wave form. Both experience and experiment seem to justify this definition, inasmuch as a tone is heard under ordinary conditions at the pitch of the fundamental, even though the fundamental and several of the lower partials are weak or missing.

The apparatus used for recording gross changes in pitch is the strobophotograph camera. Fig. 2 shows a reproduction of a record taken on this apparatus. The sound, which is picked up by a condenser microphone, is amplified and the output of the amplifier is sent, through appropriate matching transformers, into a small neon lamp. A filter is used in this circuit to reduce effectively all frequencies above five hundred, so that the lamp flashes in frequency with the fundamental of the phonated tone. This lamp shines through a stroboscopic disk containing 60 concentric rows of holes and the stroboscopic effect produced by this arrangement is photographed on a strip of sensitized paper which is drawn at a constant rate beneath the stroboscopic disk. The theory of this camera has been published[1] and will not be considered here. While the apparatus is extremely valuable in studying the melody curve in singing or playing, it is not particularly suited in its present form for recording speech because when pitch changes occur very rapidly many of the records are not legible.[3]

The other apparatus used in studying pitch supplies an accurate and legible record, although it is not so time saving as the strobophotograph

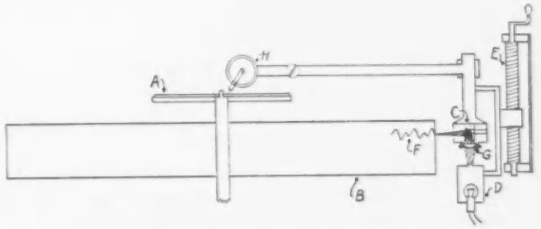

FIG. 3. Schematic drawing of apparatus for photographing sound waves from phonograph record. *A*, phonograph record; *B*, large film drum; *C*, diaphragm; *D*, light housing; *E*, screw for lowering and elevating optical system; *F*, sound wave as photographed; *G*, lens; *H*, pickup.

[3] The weakness or absence of the fundamental in speech also tends to decrease the efficiency of this machine.

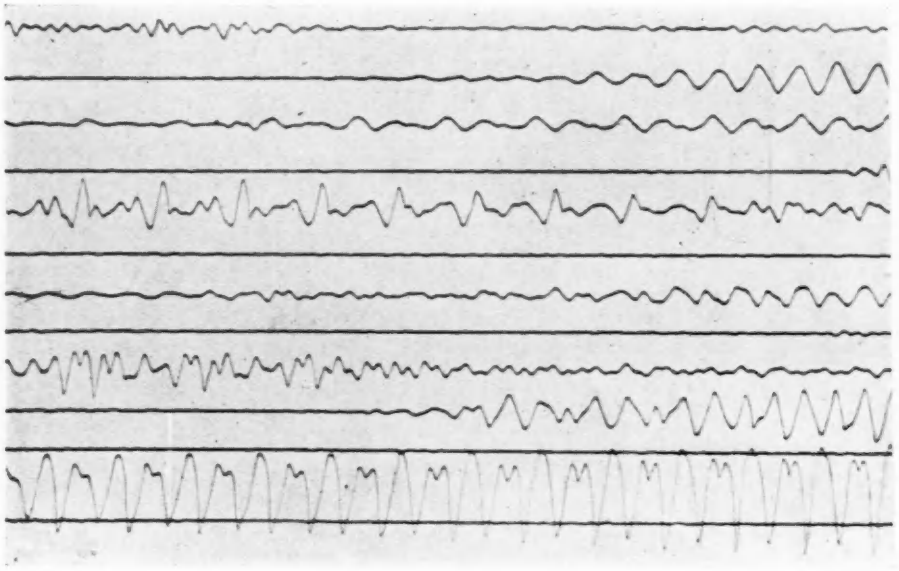

FIG. 4. Short section of sound-wave film as photographed from phonograph record.

camera. The speech is recorded on an aluminum disk which is driven by a constant speed motor. After the record is cut, the sound waves on it are transcribed to a graphic record by means of the apparatus[4] shown schematically in Fig. 3. The phonograph record is mounted on the turntable in the center of a large drum. With the room darkened, a strip of sensitized paper four inches in width is wrapped around this drum. The wave on the phonograph record is picked up by means of an acoustic sound box and transmitted through the hollow tone arm to a phonelescope, an optical lever similar to the Miller phonodeik. The beam of light from the phonelescope is focussed on the film, and, inasmuch as the phonograph record and drum are on the same shaft and move synchronously, *it makes no difference at what speed the drum is revolved.* If the record was originally recorded at 78 r.p.m., 1.3 revolutions represent one second of time and accordingly the frequency or pitch of a given voice wave is determined by dividing the wave-length as measured on the film into 1.3 times the length of the film as wrapped around the drum. A short section of film taken on the apparatus[5] is reproduced in Fig. 4. The wave is spiraled around the film so that about 20 revolutions of the record may be photographed on one strip of paper. While several other steps are used in practice, such as reading the waves in groups and plotting the wave-lengths on semi-logarithmic paper to convert the measurements into semi-tones, the above description gives the essential features of this apparatus. Repeated tests indicate that the combined errors involved in making the phonograph record, photographing the sound wave, and plotting the results is approximately 0.5 percent.

Fig. 5 shows a short section of synchronous curves of pitch and intensity variations in the voice of a well-known radio saleswoman, "Lady Esther." These curves are typical of the kind of graphs obtainable with this equipment. They were obtained from a phonograph record made directly from the radio and are typical of the speech of this announcer. Even in this short passage, a pitch range of nearly three octaves was used—a considerably greater range than is usually considered at all practicable.

Fig. 6 shows a pitch plot of Julia Marlowe speaking the mercy speech from Shakespeare's

[4] M. Metfessel, *Technique for objective studies of the vocal art*, Psychol. Monog. **36**, No. 1, 1–40 (1926).

[5] The curves taken on this apparatus are suitable only for measurement of fundamental pitch. Distortions in wave form introduced by the phonelescope make the waves unsuitable for studies of intensity and timbre. For measurements of fundamental pitch, however, these records have been found to be as reliable as high quality oscillograms.

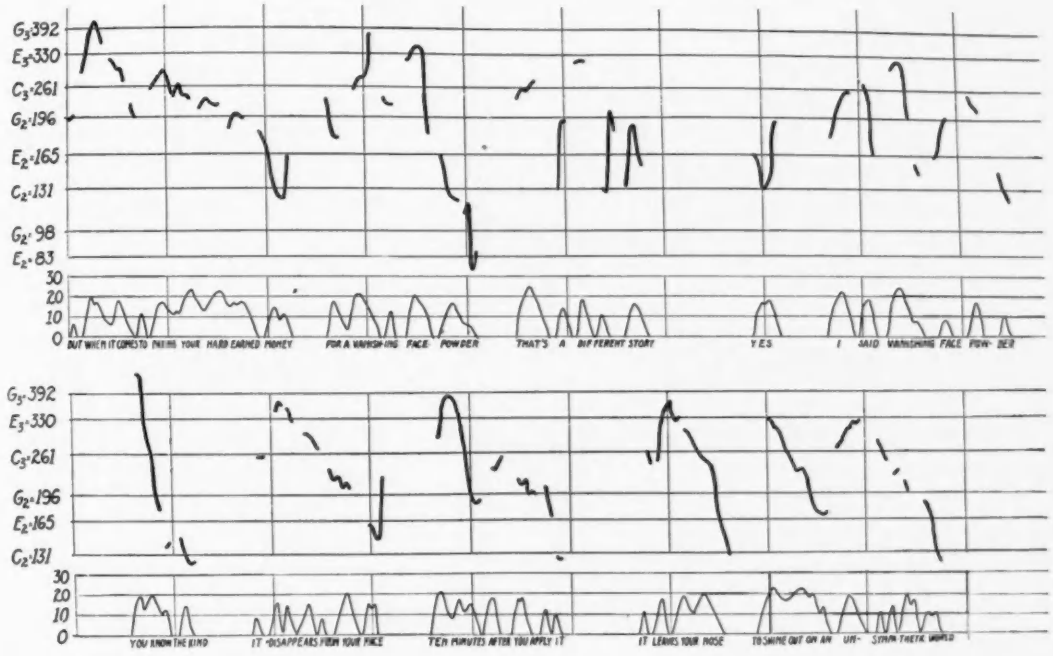

FIG. 5. Synchronous curves of pitch and intensity taken from the voice of a radio saleswoman, "Lady Esther."

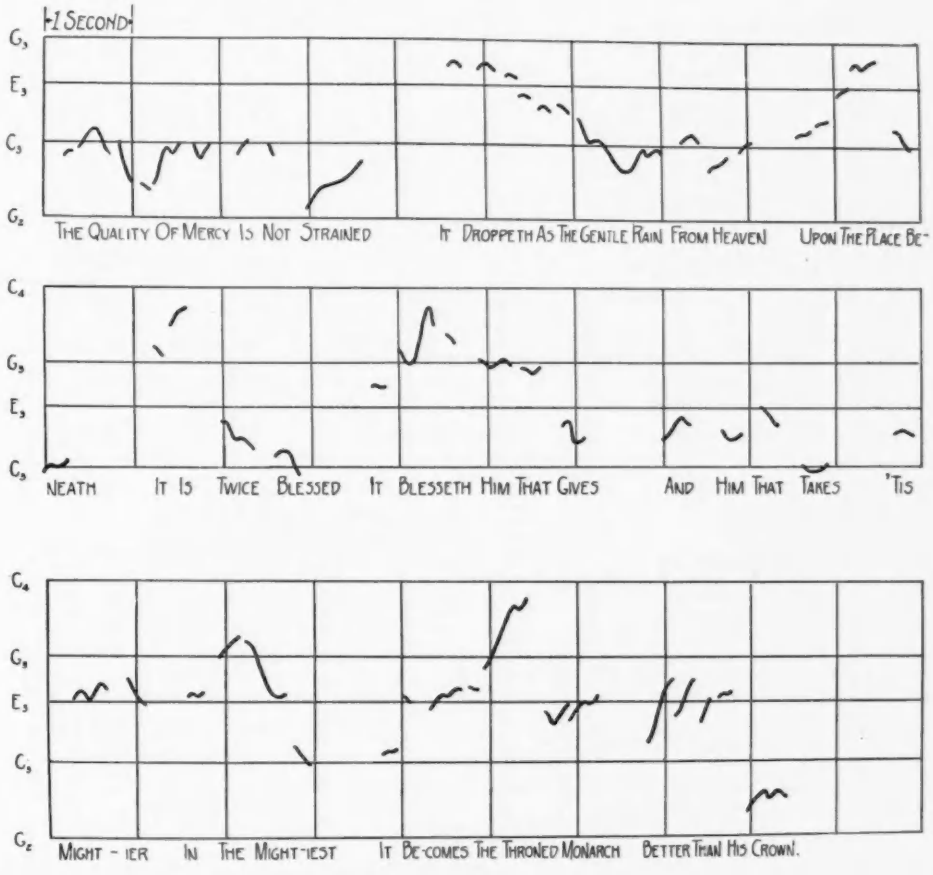

FIG. 6. Curve of pitch in the mercy speech from Shakespeare's *Merchant of Venice* as spoken by Julia Marlowe on Victor Record No. 74,678.

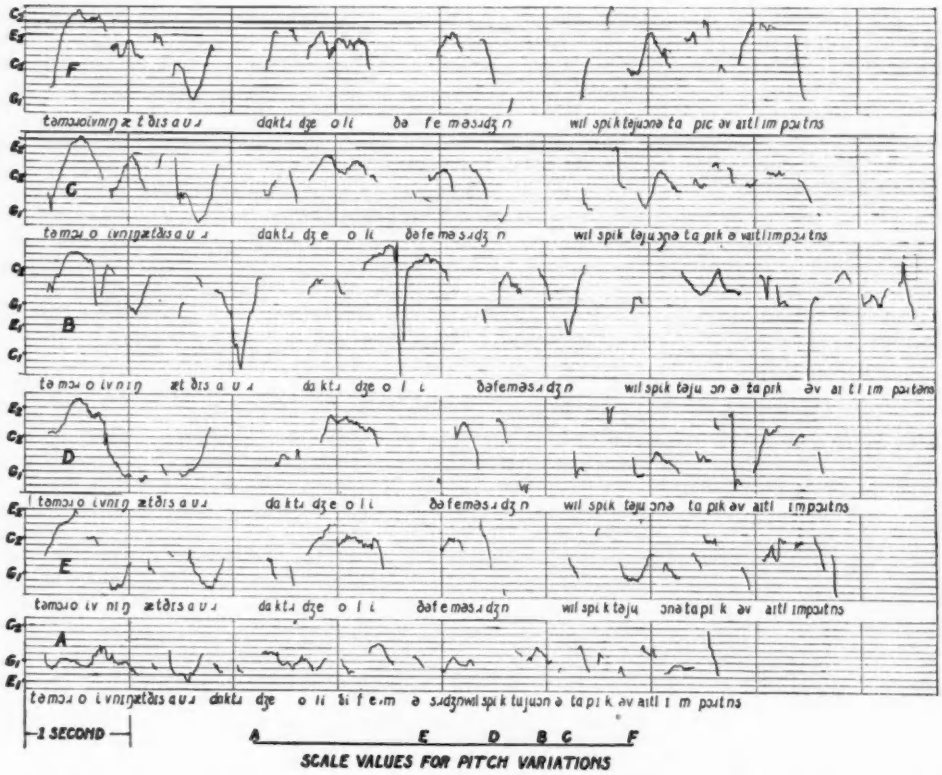

FIG. 7. Pitch curves of six voices speaking a simple informative sentence. The voices are arranged in order of judged merit (300 judges) from the top down.

Merchant of Venice as recorded on Victor Record No. 74,678. The significance of the pitch movements shown in this figure may be grasped very readily if the record is played and the curve followed with the eye.

Curves of this type are particularly valuable in studying the relative effectiveness of different types of pitch usage. In one study[6] six speakers recorded the following announcement, "Tomorrow evening at this hour, Dr. J. O. Lee, the famous surgeon, will speak to you on a topic of vital importance." Pitch curves for each of these speakers were obtained by means of the phonograph record technique described above. The voices were rated in pleasantness and effectiveness by a group of 300 students as an exercise in esthetic preference. The pitch curves were then arranged according to the ranking of these students, with the voice rated best at the top. These curves are shown in Fig. 7. A comparison of the two extremes shows that the bottom speaker used a very narrow pitch range and inflections which were both small and limited in variety. Inspection of the intervening curves, however, shows a greater difference in the form and pattern of inflections than in pitch range.

Calculation of the amount of use made of each pitch within the range covered reveals some interesting results which are shown by the distributions in Fig. 8 and are partially summarized in Table I. The distributions in Fig. 8 indicate

TABLE I. *Pitch characteristics of six voices arranged in order of merit.*

Voices in order of judged merit	Median pitch	Highest pitch reached	Lowest pitch reached	Pitch range in musical steps
1	161	208	87	7.5
2	134	185	92	6.0
3	121	175	50	11.0
4	125	175	87	6.0
5	116	165	83	6.0
6	99	117	83	3.0

[6] D. Lewis and J. Tiffin, *A psychophysical study of individual differences in speech*, Arch. of Speech **1**, 43–60 (1934).

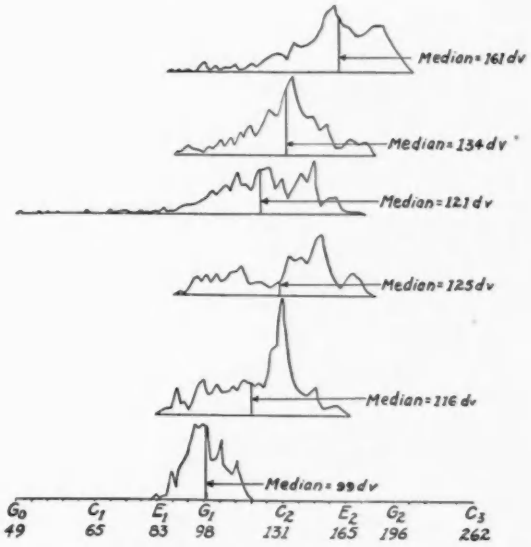

FIG. 8. Distributions showing the pitches used by the six voices whose pitch curves are given in Fig. 7. The voices are again arranged in order of merit, the best voice being at the top.

not only the pitch range utilized by each voice, but also the relative amount of use made of each pitch within this range. The voices are again arranged in order of merit from the top down. Of the six voices, the two rated best show a fairly normal distribution around their median pitches which are 161 cycles and 134 cycles, respectively. In the third voice, the fundamental sometimes extends as low as 50 cycles, and a scattering of frequencies between 50 and 83 cycles is apparent. This voice had a peculiar quality which may be appreciated only upon hearing the record. The fourth voice shows a very interested type of pitch usage which might reasonably be called bi-pitched. This speaker had a wide enough range but exhibited a strong tendency to use only the top and bottom of this range. The central pitches were functioning to only a slight degree. The fifth voice was somewhat mono-pitched because of an overemphasis of one region, and the sixth mono-pitched because of a very narrow range.

Data of this kind, particularly if the phonograph recording is also available, are a great aid to the student of voice. They yield an insight into the functioning of the pitch factor in speech which may be obtained only with great difficulty, if at all, by simply listening to the original speech.

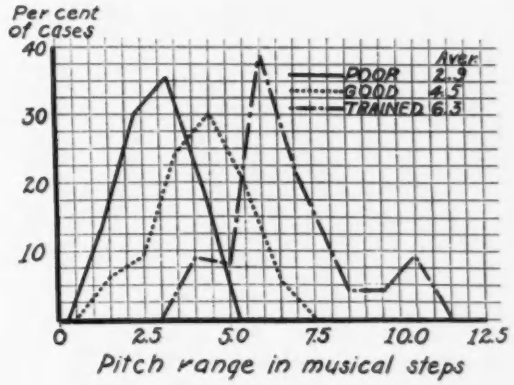

FIG. 9. Distributions showing the spread of pitch range used by the members of the three groups referred to as poor, good and trained.

In another study utilizing these techniques[7] an extended investigation was made on the pitch characteristics of 150 voices. These voices were divided into two groups, male and female, and each of these groups in turn was composed of three sub-groups. The first sub-group, labelled poor, consisted of 88 of the poorest voices from the University of Iowa Freshman class, as judged by several staff members from the department of speech. The second sub-group, labelled good, was composed of 46 of the best voices from the Freshman class according to the same criterion. The third group, labelled trained, consisted of 23 members of the staff and graduate students in the department of speech. Each subject spoke a simple declarative sentence into the microphone and his pitch curve and intensity variation curve were obtained directly. Inspection of the results showed no consistent differences in the average pitch level of the various types of voices, although there was a definite tendency for the very high pitched voices among the men to be found only in the poor group; whereas the low pitched voices among the women were found most frequently in the good group.

The results on pitch range for these three groups were quite different. These data are shown graphically in Fig. 9 and reveal a consistent increase in pitch range from the poor to the good to the trained group. The increase is so marked that there is very little overlapping between the

[7] E. Murray and J. Tiffin, *Basic aspects of effective speech*, Arch. of Speech **1**, 61–83 (1934).

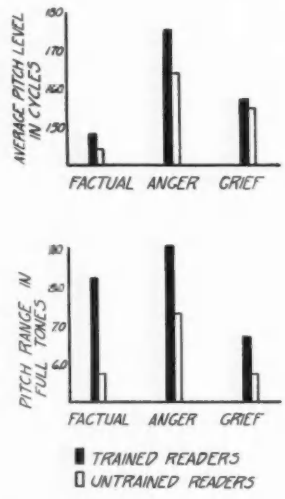

FIG. 10. Pitch characteristics of trained and untrained readers reading different types of material.

two extreme groups. Equally unequivocal were the results on average extent of pitch inflections, for this factor also shows a marked and progressive increase from the poor to the trained group. It should be borne in mind that pitch inflections may be great while pitch range is small, or *vice versa*. A person may have a wide range, but phonate each sound at a constant or fairly constant pitch. Such a speaker will have a very small average inflection. The more experienced speakers tended to use much wider inflections, i.e., to slide the pitch markedly on each phonation.

The studies mentioned above have dealt only with conversational, or, as it might better be called, factual speech. The analysis of emotional speech presents added problems but at the same time offers the psychologist a tool which is becoming almost indispensable. A section from one study[8] which dealt primarily with speech involving the expression of emotion illustrates this point. Twenty-five trained and an equal number of untrained readers were asked to read three passages. The first passage was purely factual in nature and was taken from a stage lighting catalog. The second was from O'Casey's *Juno and the Paycock*, and was intended to express intense anger. The third was from Galsworthy's *Strife* and expressed grief. The pitch range and median

[8] G. Lynch, *Study of trained and untrained speakers reading factual and emotional material*, Arch. of Speech **1**, 9–25, (1934).

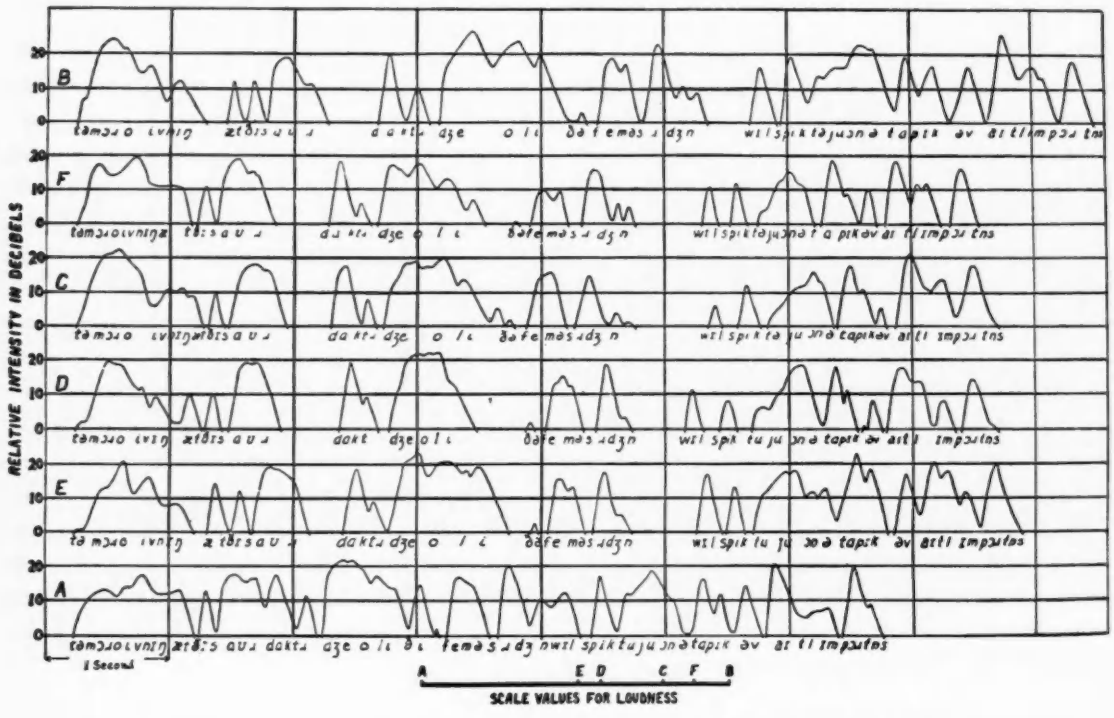

FIG. 11. Intensity curves for six voices arranged in order of merit from the top down.

pitch level for each speaker speaking the three passages were computed. The results are shown in Fig. 10. The trained group in reading each passage used a greater pitch range than the untrained, but the general changes in pitch range for the three types of material were the same for each group. For both groups of readers, the pitch range was greatest in the passage expressing anger. In the matter of median pitch or pitch level, while the trained readers pitched their voices, on the average, slightly higher than the untrained in each passage, both groups tended to increase the pitch a great deal for anger and somewhat less for grief. That persons differing so widely in training and experience tend to execute almost identical movements of pitch when expressing specific emotions is a fact of great importance to the psychologist. It indicates that vocal expression is a definite barometer of emotional experience and behavior. The physical measurement of speech waves is an approach to this field of psychology which holds promise of bringing order into a field that is somewhat chaotic at present.

We have dealt so far with an eclectic sampling of studies in pitch. A parallel approach dealing with the intensity factor may be made in almost every instance. Fig. 11, for example, shows intensity curves for six voices arranged in order of merit from the top down according to effectiveness in using variations of loudness, as judged by 300 students. These curves were taken on the high speed output level recorder and were transcribed to the decibel scale shown in Fig. 11. A decrease in variability may be noticed as the bottom curves are approached and a study of the more effective voices reveals the range and type of variations of intensity utilized by the better speakers.

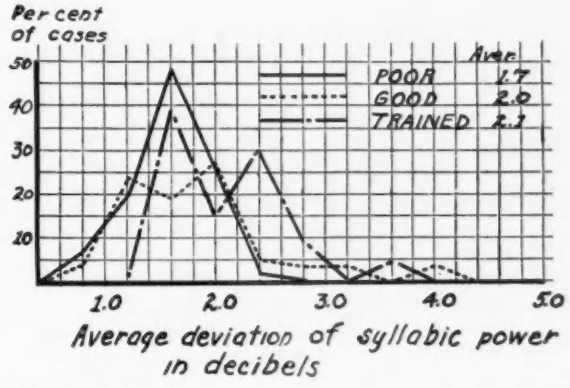

FIG. 12. Distributions showing the spread of syllabic speech power used by the members of the three groups referred to as poor, good and trained.

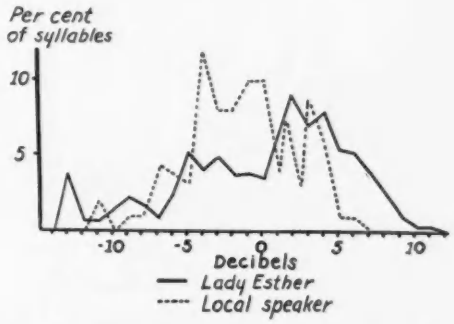

FIG. 13. Distributions of syllabic speech power for two speakers.

Fig. 12 shows the results of a related investigation dealing with approximately 150 voices which made up the three groups already referred to in the discussion of pitch as poor, good and trained. For each speaker the average deviation of syllabic power for approximately 20 syllables was computed. The three frequency polygons show the results graphically. We again note that the better groups utilize more variation in syllabic power from syllable to syllable and that the upper half of the total range in this measure contains cases only from the good and trained groups of speakers. These two groups are shown in Fig. 12 by the dotted and dash-dot lines.

The data on range of syllabic power, although obtained mainly from local speakers, were supplemented in one instance by data obtained from the speech of well-known radio announcers as received over the radio and recorded on phonograph records. It is well recognized that these latter data may be considerably distorted by the fact that the "mixer" at the broadcasting station may keep the range of intensities in the broadcast signals less than it is in the original speech. In spite of this fact, the range of syllabic intensities used by "Lady Esther," a radio saleswoman already mentioned, is considerably greater than that of any local speaker so far studied. The dotted curve in Fig. 13 shows the range and distribution of this factor for one of the most flexible voices available locally; but it will be noticed that even this voice is considerably more limited than that of the professional announcer.

Thus "Lady Esther's" use of intensity variation and her almost unbelievable flexibility in pitch markedly differentiate her from the ordinary speaker. These characteristics, in some measure, explain her success as a saleswoman.

Lowell Thomas, whose pleasing news announcements are very familiar on the air, has exceptional flexibility of intensity variations. Measurements upon a passage about one minute in duration from his voice showed a range of syllabic speech power of approximately 22 db. Randomly selected speakers show a corresponding range of only about 16 or 18 db.

In some studies in this field, the work may be fractionated and the pitch and intensity curves recorded and interpreted independently. However, it is frequently necessary to deal with these two factors at the same time. This situation is illustrated in the problem of stress. Does a good speaker stress a word primarily by making it louder than adjacent words, by raising its pitch, or in some other way? Investigations now under way indicate that one or all of three factors are used. These three are increased intensity, heightened pitch and prolonged duration of the stressed word or syllable. Contrary to general impressions the pitch and time factors seem to be considerably more pronounced and important than the increase of intensity.

This scattered sampling of studies is intended only to indicate the point of view and general methods of experimental esthetics applied to speech and voice. In the field of speech, as well as in vocal and instrumental music, we may give a complete and unequivocal description of what is considered an effective and pleasing performance. In spite of the difficulties peculiar to the problem, for the investigator must control, or at least be aware of, the conditions of speech, the training and emotional state of the speaker, the mood of the material spoken, and numerous other factors, an experimental esthetics of speech and voice seems by no means unattainable.

Motional Impedance Diagrams

T. S. LITTLER, *Department of Education of the Deaf, The University, Manchester*

(Received February 3, 1934)

The paper discusses the significance of impedance measurements on a telephone receiver. It shows how these measurements, taken when the diaphragm is prevented from vibrating, set a limit to the impedances when the diaphragm is free. From the two series of measurements, it is possible to determine the mechanical energy supplied to the vibrating diaphragm.

Power in an Inductive Circuit

WHEN an alternating current flows through an inductive circuit, the power supplied consists of two components, namely (a) the heat energy dissipated in overcoming the direct-current resistance and (b) the energy used in maintaining the magnetic field. Ohmic heat energy is active for any circuit but in a purely inductive circuit the magnetic energy is reactive. In such a circuit the magnetic flux is in phase with the electric current and consequently the magnetic current is in leading quadrature to the magnetomotive force and the result is that the magnetic energy is reactive. In this case, if the impedance of the circuit at different frequencies is plotted on a diagram, the locus is a vertical straight line, the resistance of the circuit at all frequencies being constant (Fig. 1). In general, however, in an inductive circuit, there are hysteresis and eddy losses and a vertical impedance locus is not obtained. This is exemplified in the case of the inductive circuit of a telephone receiver and Fig. 2, due to Kennelly,[1] shows how the effective resistance and effective reactance of a given receiver vary with the frequency of the testing current. The locus is approximately a straight line for the range of frequencies used.

Analysis of Vector Impedance Diagram

In Fig. 3, let OD represent the impedance vector of an inductive circuit at a given frequency f and let OA represent the direct-current resistance of the circuit.

If I is the current flowing through the circuit, then $I \cdot AD$ is the e.m.f. induced in the circuit due to the magnetic flux.

Let $AD = Z_D$, $AC = X_D$ and the angle $ADC = \beta$ and let $\mathcal{F}$ represent the magnetic flux through the circuit.

It can be seen that the flux lags behind the current by the angle β, which has been called by Kennelly, "the vector deviation angle."

The magnetic current is given by

$$J = d\mathcal{F}/dt = \dot{\mathcal{F}} = j\omega\mathcal{F} \qquad (1)$$

where $\omega = 2\pi f$ if we consider a sinusoidal variation. The power dissipated in the magnetic circuit is given by the scalar product of the magnetomotive force and $J/4\pi$ namely,

$$F \cdot \sin\beta \cdot \omega\mathcal{F}/4\pi, \qquad (2)$$

where F is the magnetomotive force. Now F is related to the flux by the equation

$$F = \mathcal{F}\rho, \qquad (3)$$

in which ρ is the reluctance of the magnetic circuit. Hence the power used in the circuit is

$$E = (\rho\omega/4\pi)\mathcal{F}^2 \sin\beta = (\rho/4\pi\omega)\dot{\mathcal{F}}^2 \sin\beta. \qquad (4)$$

The power dissipated in the circuit is also given by

$$E = I^2 X_D. \qquad (5)$$

Therefore

$$I^2 X_D = (\rho\omega/4\pi)\mathcal{F}^2 \sin\beta = (\rho/4\pi\omega)\dot{\mathcal{F}}^2 \sin\beta. \qquad (6)$$

[1] A. E. Kennelly, *Electrical Vibration Instruments*, Fig. 33, p. 68.

The terminology used in what follows is that used by Kennelly, the originator of this subject.

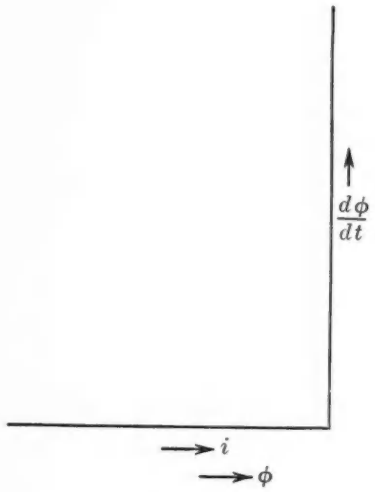

FIG. 1.

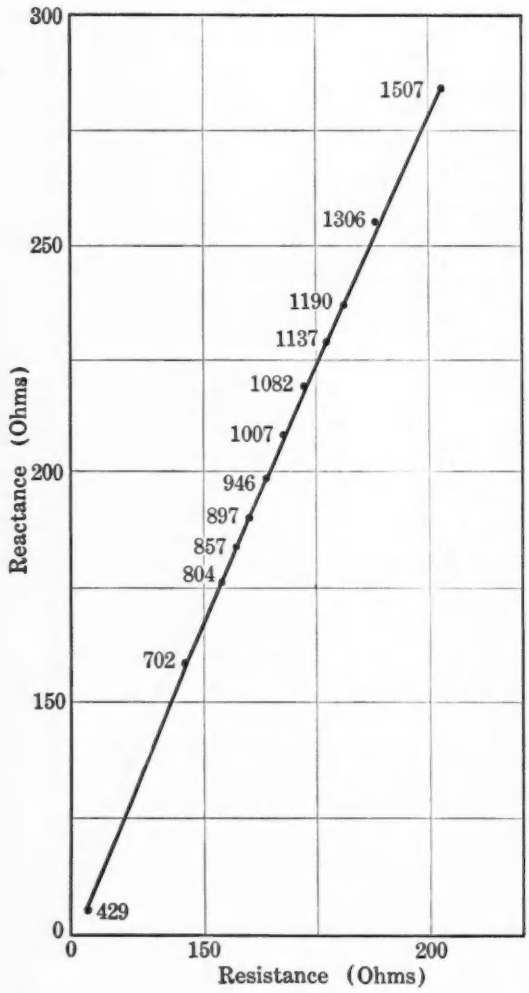

FIG. 2. Locus of vector damped impedance for tested receiver.

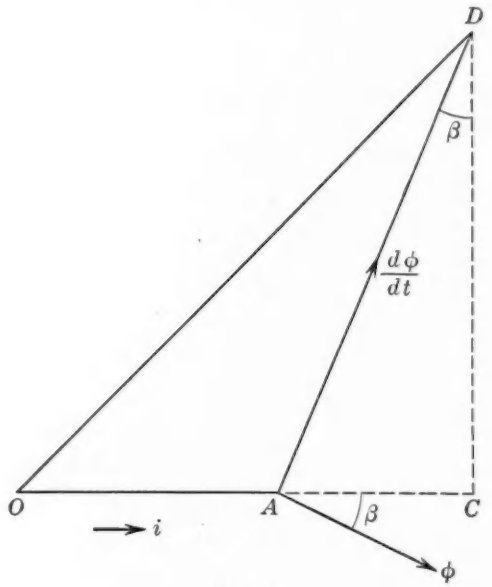

FIG. 3.

Now

$$I \cdot Z_D = N\dot{\phi}, \tag{7}$$

where N is the number of turns of the circuit. Thus a flux vector Z and a current I, that is a flux e.m.f. IZ represents a dissipation of power,

$$E = (I^2Z^2/N^2)(\rho/4\pi\omega)\sin\beta. \tag{8}$$

From (6) and (7) we obtain

$$\rho = (X_D/Z_D)(N^2/Z_D)(4\pi\omega/\sin\beta)$$
$$= 4\pi\omega N^2/Z_D, \text{ since } X_D/Z_D = \sin\beta. \tag{9}$$

It is interesting to note that this equation, when applied to Kennelly's electrical measurements for a telephone receiver, whose diaphragm was prevented from vibrating, gives a value for the reluctance of the magnetic circuit identical with that calculated by Kennelly from measurements of the dimensions of the air gap near the diaphragm.[2]

[2] Result calculated from Kennelly, *Electrical Vibration Instruments*, p. 69.

$$\rho = \frac{8\times 3.14^2\times 1.028\times 1.3^2\times 10^9}{2.35\times 10^{11}} = 0.58$$ which is same as Kennelly's experimental value p. 127.

Effect of Coupled Vibrating System

We have seen that a flux vector Z and a current I, or a flux e.m.f. IZ correspond to a power dissipation

$$E=(I^2Z^2/N^2)(\rho/4\pi\omega)\sin\beta, \cdots \quad (8)$$

$$=(I^2Z^2/Z_D)\sin\beta. \quad \text{from (9).} \quad (10)$$

This result is particularly useful in the analysis of diagrams of the impedances of circuits, as modified by the supply of energy to some other source such as a coupled vibrating system. We have an example of this in the case of the telephone receiver or loudspeaker. In such a case as this, the moving system shows itself by its effect on the flux vector, with the result that we get two impedances for the system termed the damped and free impedances.

In Fig. 4, let OD and OF represent the flux vectors when the mechanical system is damped and free, respectively.

In the damped case all the power supplied is dissipated as copper and hysteretic loss but in the case where motion is allowed there is additional power absorbed by the mechanical system.

If I is the r.m.s. current flowing we have, for the free system,

$$\text{Power supplied by source}=I^2(X+Z_F\sin\alpha) \quad (11)$$

$$\text{Ohmic power dissipation}=I^2X \quad (12)$$

$$\text{Hysteretic loss}=I^2(Z^2_F/Z_D)\sin\beta \quad (13)$$

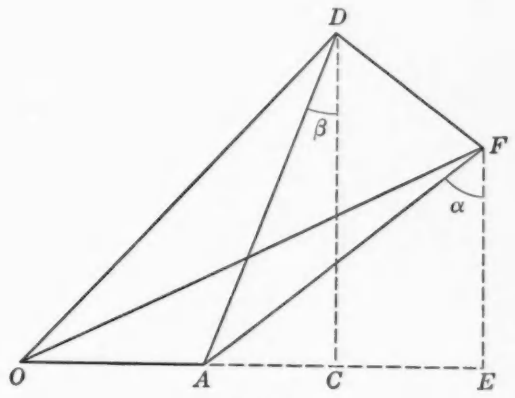

Fig. 4.

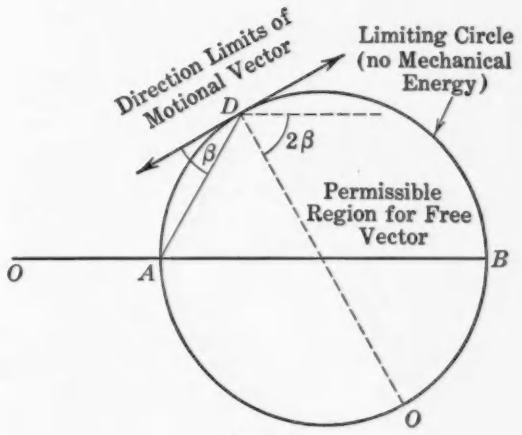

Fig. 5.

including hysteretic loss in the moving system.[3] Hence the mechanical power

$$=I^2[Z_F\sin\alpha-(Z^2_F/Z_D)\sin\beta] \quad (14)$$

$$=I^2Z^2_F[(\sin\alpha)/Z_F-(\sin\beta)/Z_D]. \quad (15)$$

This expression cannot be negative but in the case of a system vibrating without mechanical resistance it may be zero. The condition to be satisfied therefore is

$$(\sin\alpha)/Z_F \text{ is not less than } (\sin\beta)/Z_D. \quad (16)$$

We can thus assign a border limit to the point F for all permissible flux vectors. In polar coordinates it is a curve of the type $(\cos\theta)/r=$ a constant $\{=(\sin\beta)/Z_D\}$, since for a given frequency $(\sin\beta)/Z_D$ is constant. This is the equation of a circle passing through A and D and of diameter $Z_D/\sin\beta$. This result is illustrated in Fig. 5, in which AD represents the damped flux vector and AB is equal to $Z_D/\sin\beta$: If we term the vector difference between the free and damped vectors, "the motional vector," it can be seen that the tangent to the circle at D gives the direction limits of such a motional vector. The diameter

[3] This assumes, as seems justifiable, that hysteresis loss is dependent solely on the magnitude of the magnetic flux through the circuit and independent of its phase relation with any phenomenon outside the magnetic circuit.

at D has an angle of depression below the horizontal of 2β. It is interesting to note that in measurements of the motional impedances of electromagnetic receivers an approximately circular locus is often obtained and the motional vectors satisfy this condition. Our treatment made no assumptions as to the nature of the mechanical system but it can be seen that if the system is such that the motional vectors vary in direction as the frequency varies, their locus must be a closed curve which is tangential to the limiting circle at D. Further, if the motional locus is a circle, the diameter must be in the direction DO with an angle of depression 2β. This result is often obtained in the case of the electromagnetic receiver.

A number of other conclusions can be derived. Circles can be drawn within the limiting circle and touching it at D. Each of these represents the locus of free vectors having a given value of the factor $[(\sin\alpha)/Z_F-(\sin\beta)/Z_D]$. Since each diameter will represent the maximum mechanical power for its respective circle, it is clear that the maximum possible mechanical power for the system power occurs when F is at O. It can also be shown that for a given value of α the maximum mechanical energy occurs when Z_F is equal to $AB(\sin\alpha)/2$, that is when F lies on the circle of diameter AO'.

If we have a system whose effective resistance is constant at all frequencies, that is, β is equal to zero, the diameter of the limiting circle becomes infinite and therefore any free vectors are possible to the right of the damped reactance axis. As in this case no energy can be used hysteretically, the motional energy when the system is free must be the whole of the energy supplied by the source in excess of the energy dissipated in ohmic loss. If a telephone receiver were possible satisfying this condition it would have the maximum possible efficiency. The smaller the angle β the nearer the approach to this ideal. In a moving iron telephone receiver it would seem that the occurrence of a fairly large angle is due to the steel used for the permanent magnet. A fairly large field is necessary to prevent frequency doubling and to increase the sensitivity but it would perhaps be better to use an iron alloy of low hysteresis and to produce the direct field by d.c. excitation. This matter might be worth investigating considering that the hysteretic loss often amounts to much more than the ohmic loss in the circuit.

Further Analysis

In Fig. 6, let the angle $FDC=\theta$. Then the total supply of energy (other than that used in ohmic loss)

$$=I^2(AF\sin\alpha) \tag{17}$$

$$=I^2(AD\sin\beta-DF\sin\theta). \tag{18}$$

The hysteretic loss

$$=I^2(AF^2/AD)\sin\beta \tag{19}$$

$$=(I^2/AD)[AD^2+DF^2 - 2AD\cdot DF\cos(\beta-\theta)]\sin\beta. \tag{20}$$

Hence the mechanical energy

$$=(I^2/AD)[AD^2\sin\beta-AD\cdot DF\sin\theta - AD^2\sin\beta-DF^2\sin\beta + 2AD\cdot DF\cos(\beta-\theta)\sin\beta] \tag{21}$$

$$=(I^2DF/AD)[AD\sin(2\beta-\theta) - DF\sin\beta] \tag{22}$$

$$=(I^2DF/AD)[\text{projection of } AF \text{ along } DN]. \tag{23}$$

Now mechanical power where the angle $FDN=90°-\beta$ is measured by the scalar product of

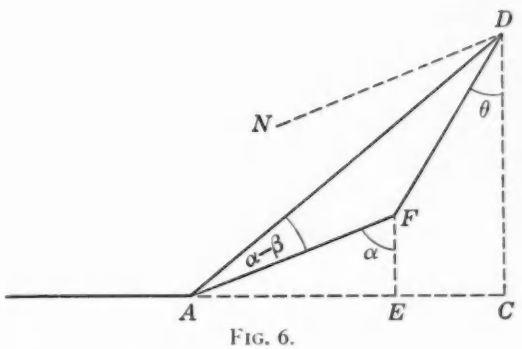

Fig. 6.

the force acting on the system and the velocity. Since $I \cdot DF$ is the e.m.f. due to the vibration of the system in the direct magnetic field, it is proportional to the velocity of the system and therefore $I \cdot AF$ is proportional to the force acting. Clearly therefore the phase angle between force and velocity is $(90°+\theta-\alpha-\beta)$. At the mechanical resonance point this angle is zero, that is, $\alpha-\theta=90°-\beta$. The point F corresponding to mechanical resonance therefore lies on a circle of which the chord AD subtends an angle $90°+\beta$. If the velocity of the system can be assumed to be $1/M$ multiplied by the e.m.f. $I \cdot DF$ then it follows from the above expression

$$\text{The force on the system} = MI(AF/AD). \quad (24)$$

Another interpretation for M therefore is the force per unit current when the system is prevented from vibrating, since in this case AF is the same as AD. This is also true for the telephone receiver when the frequency is infinitely high or infinitely low. In practice the receiver is prevented from vibrating by the application of some constraint such that the effective stiffness or the effective mass of the system is very large and this is equivalent to the application of a very high or low frequency vibromotive force.

In practice there are two main types of receivers used which are termed moving iron and moving coil respectively. It is sometimes stated that the action of the moving coil type differs from that of the moving iron in that the vibromotive force acting on the former receiver is given by a constant multiplied by the current through the coil, while in the latter case it is due to the tractive pull of the flux through the circuit. This would be true if the coil of the moving coil receiver were entirely in air but it must be remembered that the core is mainly occupied by iron partially saturated, with an appropriate vector deviation angle. We must, therefore, look upon the vibromotive force as due to the non-uniformity of the flux in the gap produced by the coil current, in which case the treatment is the same for both varieties of receivers.

For any mechanical system of one degree of freedom the ratio

$$\text{force/velocity} = 1/[r^2+(m\omega-s/\omega)^2]^{\frac{1}{2}}, \quad (25)$$

where r, s and m are the resistance, stiffness and mass constants respectively, and the phase angle between the force and velocity is $\tan^{-1}(m\omega-s/\omega/r)$.

If the mechanical system of the telephone receiver can be represented by such a simple system we have the following relation

$$\text{Mechanical energy} = (I^2/AD)AF \cdot DF \cos[\tan^{-1}(m\omega-s/\omega/r)] = (r/M^2)DF^2 \cdot I^2 \quad (26)$$

or

$$(AF/AD \cdot DF)\cos[\tan^{-1}(m\omega-s/\omega/r)] = r/M^2. \quad (27)$$

This is the equation of a circle of diameter M^2/r whose chords are of magnitude $AD \cdot DF/AF$ making angles of $\tan^{-1}[m\omega-s/\omega/r]$ with the diameter. We see that $(AD \cdot DF/AF)(I/M)$ is the velocity that the system would have if the force were a constant one of value MI instead of $MI(AF/AD)$. We expect, therefore, that if the system can be represented by constants as above, the motional impedance multiplied by the ratio AD/AF should give a circular locus of diameter M^2/r occurring at the resonant frequency $\omega_1/2\pi$ such that

$$\omega_1^2 = s/m \quad (28)$$

and the angle

$$90°+\theta-\alpha-\beta = \tan^{-1}[n.\omega-s/\omega/r]. \quad (29)$$

The ratio r/m can be determined from any other vector. Any departures from such a circular locus should show themselves as distortions of the circular locus.

It is clear from the above that we shall not expect a circular locus for the motional impedance (constant current) diagram owing to the fact that the force acting on the system is not constant at all frequencies. Also the angle made by the motional impedance vector with a given direction does not represent the phase difference between force and velocity. This is contrary to the usual treatment where in the case of an approximately circular locus the angle between the motional vector and the diameter is used to determine relations between the elastic constants of the mechanical system.

Another point seems worthy of notice. In the case of the telephone diaphragm, there are many modes of vibration and Mallett[4] has demonstrated their occurrence in practical cases. At frequencies above the first resonant frequency the diaphragm may vibrate in a mode different from the fundamental. Thus the mechanical constants will vary with the frequency of the vibromotive force. The motional impedance locus may be used to determine whether these constants vary. Since the mechanical energy of the system is given by the product of the mechanical resistance and the square of the velocity, the mechanical energy will be given by $(r/M^2)DF^2I^2$ and if we assume that M is independent of frequency, the ratio (*mechanical energy*$/I^2DF^2$) will show how r varies with the frequency.

The ratio (*mechanical energy/electrical input energy*) may be called the mechanical efficiency of the system. For telephone receivers the mechanical efficiency can be determined for the cases of constant current or constant voltage input.

TABLE I. *Damped and free impedances of a telephone receiver. Direct-current resistance =86.7 ohms. Taken from Kennelly Electrical Vibration Instruments, p. 67.*

Frequency n	ω	Resistance		Inductance		Motional	
		Free	Damped	Free	Damped	Resistance	Reactance
429	2694	130	124	41.5	38.7	6	7.5
702	4410	153	145	36.6	35.7	8	4.0
804	5052	166	153	36.2	34.7	13	7.6
857	5385	174	157	36.3	34.2	17	11.3
897	5640	184	160	36.2	33.8	24	13.5
923	5801	193	162	36.3	33.6	31	15.7
946	5941	204	163	36.3	33.5	41	16.6
962	6046	218	164	36.0	33.4	54	15.7
974	6118	230	165	35.5	33.3	65	13.5
980	6156	241	166	35.0	33.2	75	11.1
987	6200	254	166	33.6	33.2	88	2.5
994	6245	270	167	31.0	33.1	103	−13.1
1000	6283	283	167	27.0	33.1	116	−38.3
1007	6328	278	168	21.5	33.0	110	−72.8
1014	6370	261	168	17.2	33.0	93	−100.6
1020	6412	224	168	14.2	32.9	55.5	−119.9
1028	6461	191	170	14.5	32.8	21	−118.2
1036	6508	164	170	16.6	32.8	− 6	−105.4
1043	6552	151	171	19.4	32.7	−20	−87.1
1050	6597	148	171	21.8	32.6	−23	−71.2
1066	6698	144	172	25.0	32.5	−28	−50.2
1082	6798	148	173	27.3	32.4	−25	−34.7
1108	6966	153	175	28.7	32.2	−22	−24.4
1137	7145	159	177	29.5	32.0	−18	−17.9

TABLE II. *Calculation of mechanical energy from experimental results of Table I.*

(1) n	(2) ω	(3) β	(4) $Z_F \sin\alpha$	(5) $2\log Z_F$	(6) $\log Z_D$	(7) $Z_F^2/Z_D \sin\beta$	(4)–(7)	Mechanical efficiency %	Z_m^2	Mechanical energy $I^2Z_m^2$
429	2694	19 41	43.3	4.1576	2.0444	43.7	—	—	92	—
702	4410	20 19	66.3	4.4836	2.2249	63.0	3.3	2.16	80	0.041
804	5052	20 43	79.3	4.5992	2.2729	75.0	4.3	2.59	227	.019
857	5385	20 54	87.3	4.6614	2.2948	83.0	4.3	2.47	417	.010
897	5640	21 2	97.3	4.7087	2.3100	89.9	7.4	4.02	758	.0098
923	5801	21 8	106.3	4.7456	2.3200	96.0	10.3	5.32	1208	.0085
946	5941	20 58	117.3	4.7800	2.3286	101.2	16.1	7.89	1957	.0082
962	6046	20 57	131.3	4.8102	2.3348	107.0	24.3	11.1	3162	.0077
974	6118	21 2	143.3	4.8307	2.3389	111.4	31.9	13.9	4407	.0072
980	6156	21 12	154.3	4.8467	2.3409	115.9	38.4	15.9	5748	.0067
987	6200	21 4	167.3	4.8535	2.3435	116.3	51.0	20.1	7750	.0066
994	6245	21 14	183.3	4.8518	2.3459	116.1	67.2	24.9	10780	.0062
1000	6283	21 6	196.3	4.8282	2.3482	108.7	87.6	31.0	14927	.0059
1007	6328	21 16	191.3	4.7412	2.3505	89.2	101.1	36.4	17400	.0058
1014	6370	21 9	174.3	4.6274	2.3530	67.9	106.4	40.8	18779	.0057
1020	6412	21 12	137.3	4.4338	2.3547	43.4	93.9	41.9	17450	.0054
1028	6461	21 28	104.3	4.2936	2.3574	31.6	72.7	38.1	14411	.0050
1036	6508	21 19	77.3	4.2465	2.3602	28.0	49.3	30.1	11146	.0044
1043	6552	21 28	64.3	4.3077	2.3623	32.3	32.0	21.2	7986	.0040
1050	6597	21 24	61.3	4.3886	2.3636	38.6	22.7	15.3	5598	.0041
1066	6698	21 24	57.3	4.4948	2.3690	48.7	8.6	6.0	3304	.0021
1082	6798	21 24	61.3	4.5822	2.3740	58.9	2.4	1.3	1829	.0016
1108	6966	21 30	66.3	4.6474	2.3821	67.5	—	—	1079	—
1137	7145	21 33	72.3	4.6961	2.3907	74.2	—	—	644	—

[4] Mallett, Proc. Phys. Soc. **36**, 114–211 (1924).

Application to Kennelly's Results

The results of the above investigation have been applied to the observations used by Kennelly to illustrate the treatment in his textbook.[5] The angle β has been determined for each frequency by calculating the slope of the vector difference between damped impedance and d.c. resistance. It is found to increase with frequency. The calculated mechanical energies for a number of the test frequencies are given in Table I, together with the mechanical efficiency. It will be observed that at the frequency which is near the frequency of maximum mechanical energy (termed by Kennelly the gross resonance of the system), the calculated mechanical efficiency is 40.8 percent. It is interesting to note that Kennelly found the value of 40 percent for the net mechanical efficiency at this frequency by a more complicated method, requiring further measurements. Column 11 of Table II gives the ratio of the mechanical energy to the square of the motional e.m.f. and this is a measure of the factor r/M^2. The analysis is not satisfactory for the results at the extreme frequencies, where the differences between free and damped values are very small. In certain of these cases negative values are obtained for the mechanical efficiency.

The method has been put forward as a simple way of determining approximately the mechanical energy of the vibration of a telephone receiver diaphragm. In a later paper it will be shown how it may be applied to the calculation of the acoustic output of a receiver when impedance measurements are possible in air and vacuo.

I am indebted to Professor A. E. Kennelly for his helpful criticism of the paper.

[5] Kennelly, *Electrical Vibration Instruments*, p. 67.

Phonetic Distribution in Formal American Pronunciation

CHARLES H. VOELKER, *The Ohio State University, Columbus, Ohio*

(Received December 20, 1933)

WILLIAM DWIGHT WHITNEY, Professor of Sanskrit and Comparative Philology at Yale College, in 1874 was the first phonetician to make a study of the relative occurrence of speech sounds in English. He based his frequency distribution count of the sounds of speech on a selection of ten passages, five in poetry and five in prose, of ten various authors, of ten various periods, and separated and counted the individual sounds as met with in each, until the number of 1000 sounds was reached. Taking 1000 sounds from each of ten passages makes 10,000 sounds for the entire study.

Whitney took these sounds, he says, "Of course for my own pronunciation; but the principal data may be taken as belonging, nearly as given, to the general language." To justify this thesis, he adds, "It should be noted that the number given for *r* represents the more accepted pronunciation, rather than my own natural one (which would leave, . . . 370 of the 744 cases unpronounced)." To make his own pronunciation general he offers only this one allowance.

The second tabulation of the relative occurrence of speech sounds was not made until almost half a century later, by Godfrey Dewey, in 1923. Dewey took up this study as a result of his interest in shorthand, in the literature of which subject, he found no study of the frequency of occurrence of the sounds. He says:

> The literature of shorthand contains singularly fragmentary statements with respect to sounds, which agree chiefly in recognizing the preponderance of the 3 consonants, *n*, *t*, *r*, which Isaac Pitman called "the bones of the shorthand skeleton."

On Dewey's technique of gathering material he states:

> The first step . . . was to select 100,000 words of connected matter adequately representative of good English as used—written, spoken and printed,—today.
>
> 15% newspaper editorial English
> 15% newspaper news English
> 15% modern fiction
> 10% modern American speeches
> 5% personal correspondence
> 5% business correspondence
> 5% modern advertizing
> 5% religious English
> 5% (popular) scientific English
> 5% modern 'special articles'
> 5% magazine editorial English
> 5% Saturday Evening Post
> 5% Literary Digest

Dewey says:

> . . . it was necessary to have (a) a definite authority for pronunciation; (b) an explicit and unmistakable fonetic notation; and (c) particularly for the third and fourth stages to follow, a definite linear order for the fonetic alfabet.
>
> The *Standard Dictionary* (Funk and Wagnalls, New York) was chosen as the only possible authority for such an investigation by reason of its use of the Revised Scientific Alfabet (popularly known as the N E A key alfabet) for indicating pronunciation.

The dictionary does not indicate connected pronunciation, but merely that of isolated words. Phoneticians must surely agree that we at least depart from dictionary standards in connected speech. It is a natural law of language, for sounds tend to be modified, added, or dropped, when the words in which they occur are used in connection with others on either side of them, especially as they occur in normal speech.

Another study of the relative occurrence frequency of phonetic sounds was made in the technical research laboratories of the Bell Telephone Company, by Norman R. French, Chas. W. Carter, Jr., and Walter Koenig, Jr., in 1930. They describe their technique as follows:

> The material for the . . . study was obtained from telephone conversations over typical toll circuits terminating in the city of New York. The process of noting the words of the conversations was carried out in the following manner. During one week the observer recorded nothing but the nouns used, during another week she recorded only verbs, and during a third week only adjectives and adverbs. This routine was repeated until observations had been made on

500 conversations for nouns, 500 conversations for verbs, and 500 conversations for adjectives and adverbs. Three other classes of words were recorded: prepositions and conjunctions, pronouns, and articles; but for these classes approximately 150 conversations in each case were judged to be sufficient . . .

Certain classes of words were, for various reasons, omitted entirely. . . .

It was not feasible to record the original words phonetically, just as they were pronounced by the telephone subscriber. Instead the words were recorded and their phonetic values assigned later. . . . The . . . words were each assigned a single pronunciation selecting that which we regarded as being typical pronunciation heard in reasonably enunciated conversation among educated persons in New York.

No comment is needed on the authors' substitution of their own pronunciation of isolated, unconnected word lists recorded stenographically for them by an operator so that they did not hear them as they were actually spoken. First, the subjective impression of the authors can well differ very materially from the actual pronunciation of the different speakers. Especially where they consider words separated violently from their context. Second, words in a continuum of conversation are changed radically by sounds which fall on either side of them. They say, "The departures from dictionary standards are largely confined to the vowels." But many phonetic scholars will undoubtedly insist that severe modifications in consonantal elements occur in normal speech: not only due to the influence of contiguous sounds in nearby words; but by reason of intonation rhythms; sentence stresses (both duration, pitch and loudness); varying emotional modulation; as well as breath group and sentence pauses.

In 1931, Dr. Lee Edward Travis, Professor of Psychology and Director of the Psychological and Speech Clinic in the University of Iowa, made a study of the frequency of occurrence of speech sounds. He was interested in the subject as a lalo-phoniatrist, because as he says, "Possibly a child has difficulty with a certain sound largely because he seldom hears it." Professor Twitmeyer of the Psychology Department and Speech Clinic at the University of Pennsylvania had this in mind when he had his assistant, Nathanson, develop a series of therapeutic speech exercises on the basis of Dewey's results.

Travis made a study of the sounds occurring in conversational speech. He says:

From children and adults in various walks of life a great many casual conversations were phonetically recorded. The speech of each person tested was thus observed and recorded over a period of at least three hours.

Travis' count was based on 16,077 sounds. French, Carter and Koenig of the Bell Telephone Laboratories claim that 10,000 are sufficient, but give no evidence for this statement.

Hill, Gutzmann, Calzia, et al., have studied the voice sounds of young children. Grandgent and many others have studied American speech, indicating the phonetic sounds employed in the various dialects. But these isolated articles have nothing to do with frequency distribution counts.

It was felt that two studies were still needed. One of current speech exactly as the individual pronounced it over the nation at large. The other of what may be considered a norm for at least one type of fairly generally accepted "careful," cultured, or perhaps what we may better designate as "formal" American pronunciation. Since the Bell Laboratory count clearly falls in the first category, our attention was turned to the latter as the most needed.

Radio announcement speech was selected for this study of formal American English, because announcers are quite comprehensively distributed. In fact the entire United States was fairly well represented. They come from a great variety of localities, belong to many speech environments, may be considered as approaching the norm for typical, perhaps the most widely accepted type of formal American pronunciation and tend to follow and to some degree might conceivably have some influence on speech trends. They had no suspicion that their voices were being recorded and so would not be tempted to alter their ordinary pronunciation. Selections recorded were representative of reading, oratorical, extempore and impromptu styles.

Five thousand nine hundred forty-six radio announcements were studied. The announcers name was procured by letter from the station after his program had been recorded.

Not more than three records of the same announcer were used. In cases where more than one record was used, each record represented a slightly different type of speech.

A personal letter was sent to the announcer, sometimes followed by a questionnaire, when insufficient or no information was received in response to the letter. In answer to these, he listed the factors he thought came into play to influence his pronunciation.

Approximately sixty percent gave this information. The most common influences among the announcers were: college training, theatrical experience, training in dramatics, speech, voice, music, diction or phonetics. Some gave history of living most of their lives in one section of the country, others of extensive travelling. Most of the announcers were native born, but record was found of homes in London, France, Canada, Mexico, Austria, Czechoslovakia, Scotland, Hawaii, other islands of the Pacific, etc. Some mentioned that their parents were from Ireland, Lithuania or England, etc. Others suggested that their enunciation was influenced by having been educated in a foreign tongue, southern pronunciation, "Canadian English," "Pennsylvania Dutch" accent, mid-western pronunciation, or "London" speech, etc. Localities from almost all parts of the United States were represented. So the selection of speeches is probably representative of formal American speech.

In order to procure a diversity of material, station announcements such as: "Your station is —," or "This is radio station —," could not be used. It was therefore necessary to select only announcements of advertising, entertainment or other such programs. Examples of their reading of both prose and poetry are also included. Since radio is on a commercial basis, announcements of necessity are, in many cases, of extremely short duration. A selective minimum was determined at a continuum of one hundred speech sounds per recording. It would seem a meager number per case when the number of phonetic symbols to be divided into that one hundred sounds is considered. However, it is not the quantity of sounds sought, but exactly which sounds occur.

The announcements were recorded phonographically through a vertical cut electrical recording head constructed in our own laboratories, the speech being thereby recorded directly from the radio onto a wax record. The quality of the system was high enough to satisfactorily record distinctions between *s* and *sh*. It was much superior to the commercial telephone, though of course it had the well-known deficiencies especially on alternated consonants in final position.

These records were played and replayed until certainty as to just which sounds occurred could be ascertained. These sounds were then transcribed phonetically. In order to stabilize the human equation as much as possible, the observers not only went through a period of training in recording speech sounds from this type of record, but were selected only if their hearing acuity as shown by Western Electric 2-A audiometer test was normal on all tones. Each record was transcribed by three observers working independently. The results were compared and differences rechecked until an agreement was reached.

The observers transcribed sound by sound from the records, without reference to meaning, attended only to those sounds actually reproduced. Since the observers' ear was the criterion of judgment in all cases, a too narrow transcription would only lead to untold disputes and difficulties besides slowing the work up beyond practicability. A broad transcription was therefore used.*

Five thousand nine hundred forty-six announcements were studied in which six hundred sixty-five thousand ninety-four sounds occurred.

The occurrence of each sound was counted and the data tabulated into frequency distribution tables. The relative percentages of occurrence of each sound were determined and compared. The resultants pertaining to moot words, etc., are not

*_Note:_ Needless to say, the sounds were transcribed in International scientific symbols, most of which have been accepted, understood and used by scientists the world over for centuries now. They thus need no interpretation in the light of key words, which themselves are so differently pronounced by individuals with varying pronunciations. For they represent values as universally understood as are those of chemical symbols. Common English orthographic symbols could obviously not be used because many of the letters of that alphabet stand for more than one sound, *viz.*, "o" as in *not, cold, loft, brown, foot, loose, monk, rouge, round, boil,* etc. Furthermore, common spelling was not feasible for the reason that, as is well known, we do not speak with words but in word groups or breath phrases, so that some of the sounds which make up the words are changed or drop out entirely, or even are supplemented by new sounds which enter in as a result of assimilation.

being studied, since the word as an entity was purposely disregarded.

Table I lists the phonetic sounds of English in order from the most to the least frequent number of occurrences in the speech of formal American English. Extreme difficulty was encountered in determining whether such vowels as in the word intens*i*ty were pronounced as *I*, or *ə*. They are therefore listed together in the table as well as separately. The distinction between the vowels in p*u*p and th*e* (i.e., *a*bove) is also dubious, so they are likewise so treated. Many consonant assimilations are also undoubtedly missed but they are not so amenable.

Assuming that the vowel in *pip* was never confused with *ə* it may be said it was the most frequent sound of all, occurring almost eight percent of the time. That frequency may well be in no small measure responsible for the tendency of this vowel *I* to oppose the general trend of all other vowels in unaccented syllables and small proclitic position words to turn into *ə*. In spite of that fact, however, this latter is far and away the next most common, for it occurs almost twice as often as its next nearest competitor. Does it not seem a pity that ordinary spelling has no letter to represent it. The antiquity of the sound not only in English but in parent languages is now well attested. It is also of interest to note that it is probably the second sound the baby learns to use. Its cry on æ being the first.

At the beginning of the study the affricates were counted separately since they had been transcribed into their elements. The transcriptions were made in breath groups, separating slightly intermediate pauses. These intermediate pauses did not always occur at the end of words, but often not until after a half dozen words; sometimes this pause even occurred in the middle of a word. Of course, many of the words were mutilated, through sounds being dropped, added, or changed. The ordinary conception of syllable division was utterly destroyed and naturally this permitted many more affricates than the so-called "*ch*" and "*j*" sounds which some think of as the only ones in English. When this problem of tabulating fine distinctions arose, the whole affricate idea had to be dropped as a practical impossibility. The ordinary affricates, therefore, are not given in the tables, but appear only as their separated elements.

The first sound in *whip* and the "*zh*" sound in *azure* occurred with the least frequency. The "*th*" in *thin* was the next least frequent.

The sounds occurring relatively from 1.0 to 1.1 percent were the initial consonants in *ship* and *yes* and the first consonant in *ping*.

The voiced ð in *the*, the vowels in *pap*, *pep*, and *peep*, and the nasal in *mit* occurred with about equal frequency.

The indefinite vowel was quite common, appearing fourth in the list, occurring six percent

TABLE I. *Relative frequency distribution of 660,594 sounds in the English of 5946 radio announcements.* (Broad transcription.)

Phonetic sounds I.P.A.	Key words	Number of occurrences	Relative frequency percent
I and *ə*	p*i*p, id*ea*	97018	14.68
ʌ and *ə*	p*u*p, id*ea*	47800	8.22
ʌ, *ə*, and *U*	p*u*p, id*ea* and p*u*t	59448	9.98
I	p*i*p	52055	7.88
ə	id*ea*	44963	6.80
ʌ	p*u*p	2837	.42
U	p*u*t	11648	1.76
n	*n*ip	48387	7.32
t	*t*ip	47589	7.20
r	*r*ip	42913	6.49
d	*d*ip	33793	5.11
s	*s*ip	30799	4.66
a	p*o*p	27457	4.15
l	*l*ip	25785	3.90
ð	*th*e	20929	3.16
æ	p*a*p	20417	3.09
ɛ	p*e*p	20206	3.05
i	p*ee*p	18713	2.83
m	*m*it	18245	2.76
k	*k*ick	16945	2.56
f	*f*it	14207	2.15
z	*z*ip	14198	2.14
ɔ	p*aw*p	14114	2.13
o	p*o*pe	14016	2.12
e	p*a*pe	13189	1.99
u	p*oo*p	13189	1.99
b	*b*it	12986	1.96
w	*w*it	12218	1.84
h	*h*it	10848	1.64
v	*v*im	10238	1.54
p	*p*ip	9828	1.48
j	*y*es	7709	1.16
g	g*o*	7134	1.08
ŋ	pi*ng*	6847	1.03
ʃ	*sh*ip	6677	1.01
θ	*th*in	4336	.65
ʒ	a*z*ure	2726	.41
ʍ	*wh*ip	2465	.37
Total		660,594	99.73

of the time as did also the "*r*" sound. Whether the "*r*" occurred linguistically as a consonant, semi-consonant, syllabic consonant, or vowel form, it was considered acoustically and treated as a single phoneme, regardless of position, or variation in quality.

The consonants sounds "*f*" and "*k*" and the vowels in *paw* and *pope* occur about an equal number of times. The vowels *nape* and *boot* occur an equal number of times, "*b*" occurring almost as often.

The "*d*" sound alone occurs five percent of the time. The "*s*" sound and the vowel in *pop* both occur four percent of the time.

The consonants occur more than one-fifth as often as do the vowels. Relatively 61.8 percent of the sounds spoken are consonants, that is, using a broad classification of consonants including semi-consonants, etc. On the other hand, only 38.2 percent of speech is comprised of vowel sounds.

All vowel and consonant so-called diphthongs are separated into their actual components as transcribed by the observers, without regard to theories of grammarians and philologists.

Only six consonants, "*n*," "*z*," "*r*," "*d*," "*s*," and "*l*" make up 50 percent of the consonants, and ten consonants make up almost three-fourths of all of them, so that the remaining thirteen consonants appear only one-fourth of the time in speech.

The voiced consonants are more frequent than the unvoiced ones, but not so much more as one might be led to believe. The unvoiced sounds occur only a little over a third of the time, 35.2 percent. Of course, there are not so many whispered sounds as voiced ones, only nine out of twenty-three being whispered. Therefore, there are only 4 percent more voiced consonants than whispered ones after weighing the respective groups.

First Preliminary X-Ray Consonant Study*

G. OSCAR RUSSELL, *The Ohio State University, Columbus, Ohio*

(Received February 17, 1934)

IT is now very obvious that long sentences in normal speech which contain a large number of other consonants cannot be adequately studied by the palatographic[1] and other such procedures heretofore utilized, for each succeeding consonant would make its record on the palate and thus obliterate that of the consonant one desires to study. While past studies may be valid for limited initial or intervocalic consonants, only certain short more or less artificial words must be chosen. Even a large percentage of the vowel combinations must be eliminated, and only those which make no palatographic contact can be used. Then too, one is limited to a single isolated word out of its thought and sentence context. Since speech is not made up of such isolated words or sounds, but consists of a large number of these combined in various orders and in such a way as to very radically affect each other, the question must always arise as to just how much value these former studies have. Furthermore, as I have repeatedly pointed out, the back pharyngeal cavity seems to be of quite as much importance as the front buccal cavity, and the palatogram only shows the front mouth phenomena. Besides, for that same reason it is now evident that the median section in perpendicular plane is the only picture of the cavity which will give the most basic facts of interest concerning any speech sound. But the palatogram indicates the horizontal plane and both it and Meyer's more adequate perpendicular plastographic linguagram[2i] record but a part of the vocal cavity. The procedures of Grandgent[2b] and Atkinson[2f] are undoubtedly less reliable than the latter, though all of them indicate the sagittal median section line.

The x-ray photograph taken from the side of the head is much better, for it gives the complete median section measurement of the cavity from its beginning to the final aperture at the exit, along the line of widest opening. The only question is whether one would be able to rely on a picture made of such consonants where the exposure is prolonged. For any such prolongation would naturally make it artificial. Yet with one exception,** so far as the author has been able to discover, all physiological studies of the consonant have been of this type.

The first x-ray photographs we attempted in our laboratory were also of this nature. The results thus obtained were presented in St. Louis a number of years ago. And it may be said that they seemed to indicate so few basic facts governing any theory pertaining to consonantal quality differences as to hardly justify the expenditure and effort necessary in order to make the study. In general, they seemed to show that the consonant had a quite definite position and cavity capacity regardless of the vowels on either side of it. And one seemed justified in assuming, therefore, that if the vowels modified that position materially the resultant consonant might be changed into something approximating quite a different one.

The results obtained by such a technique in which the consonant occurs between two vowels and is prolonged a sufficient length of time to permit the operator to make the exposure, are shown in Figs. 1 and 2.

Fig. 1 is a photograph of the **z** as it occurs in the word **easy**. Whereas Fig. 2 is a photograph of the same sound as it occurs in **ozone**. When these two pictures are superimposed as in Fig. 3

* All black faced isolated letters used herein represent sounds with fixed values. International scientists the world over have used them with these given predetermined and fixed values for hundreds of years now,—for a longer time even, and with the same mutual and international understanding as chemical symbols have been used among chemists. Your author makes a plea for the same standardization in all articles published in this journal.

** The x-ray motion pictures of Gutzmann referred to at the end of this article.

FIG. 1. Prolonged **z** as it occurs in the word *easy* (**izi**).

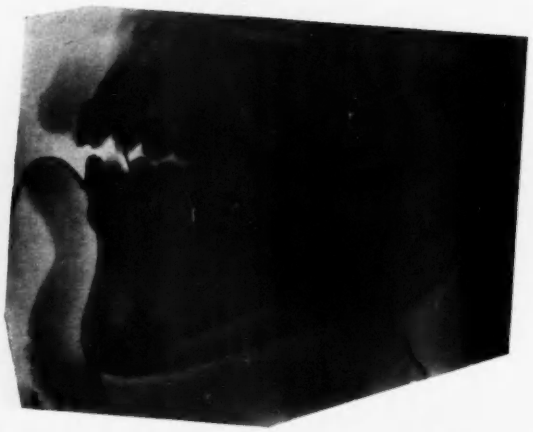

FIG. 2. Prolonged **z** as it occurs in the word *ozone* (**ozon**).

FIG. 3. Tongue positions of Figs. 1 and 2 superimposed, and shown to be almost identical for both prolonged **z**'s regardless of the vowels on either side, which is not true in normal speech.

one observes immediately that the tongue position is that of neither an *e* (**i**), nor an **o** (if we assume that either of these vowels has a fixed characteristic position of its own). Nor is there any material difference between the two. The jaws even show the same amount of separation. And at no point does the tongue line deviate more than 4 millimeters from that of the other. The hyoid bone has changed its position somewhat, but even the lips and velum as well as the tip of the epiglottis show essentially the same position. One might even be constrained to say that the one picture was an exact duplicate of the other instead of the two being made at different times, of a consonant in entirely different vowel surroundings.

Now let us observe, however (see Fig. 4), what happened to this same consonant under identically the same circumstances except that we make the picture of the consonant as it occurs in normal speech. That is in a word which is a part of a regular long discourse where the subject is permitted freedom to continue talking after the exposure of 1/128 second is made, without paying any attention whatever to either the operator or a need for holding the position in order that the exposure might be taken. In this case the exposure is automatically made at 1/128 sec. of the **z** in normal pronunciation as it occurs in **easy** while the subject is using it in such a sen-

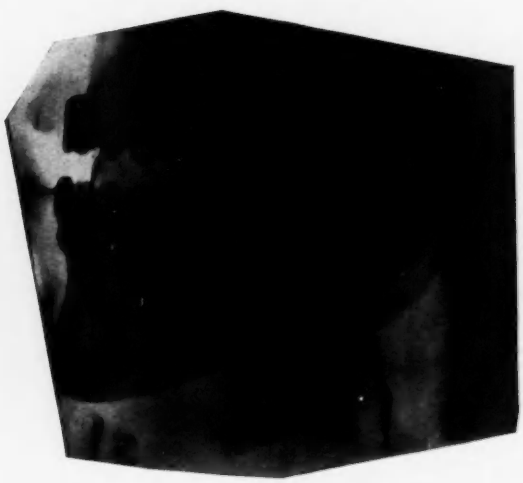

FIG. 4. Normal speech **z** in the **izi** combination as it occurs in the sentence pronounced with normal rapidity: "*Oh he's* **easy** *enough to see if you go about it right.*" 1/128 of a second x-ray exposure, automatic at the exact moment of maximum contact. Subject unaware of what is being tested.

tence as: "*Oh, he's* **easy** *enough to see, if you go about it right and make the appointment ahead of time.*" It will be seen now that the tongue position for the **z** is essentially that for the vowel *e* = (**i**), except at the point where the tongue comes in contact with the alveolar ridge. In both Figs. 1 and 2 the tip of the tongue was up. But in this Fig. 4 taken during normal speech it will be seen that the contact is between the blade of the tongue at least two centimeters back from the tip, if I interpret my x-ray correctly. And further, that the tip rests well down below the cutting edge of the lower teeth. The back pharyngeal cavity is wide open and there is not the slightest tendency for the back part of the tongue to approach the velum. Furthermore, its arching shows an abrupt drop downward approximately in the neighborhood where the hard and soft palate join.

On the other hand, when this **z** occurs, in combination between the two vowels **o** on either side of it, quite different results are shown. This can be seen by reference to Fig. 5. The exposure was made of a **z** in the sentence: "**Oh Zoe** *will be there in plenty of time for she is never late.*" Now it will be seen that the back pharyngeal cavity is much reduced in diameter, being no bigger in median section than a pencil. The main body of the tongue lies flat in the mouth almost on a level with the cutting edge of the lower teeth. It begins its arch or bends forward into the buccal cavity almost under the pillars of the fauces where they attach to the velum. The front buccal cavity is wide open. It is also very much larger than for the **z** before two vowels *e* = (**i**), in Fig. 4, and the tip of the tongue is the part which makes contact with the alveolar ridge; the blade is in nowise involved.

Furthermore, an astounding observation is made in regard to the position of the teeth. In the past we have been accustomed to think of the buzz being radically accentuated by reason of the contact between upper and lower teeth. And likewise to think of the jaw being more closed for the vowel *e* = (**i**) than for the **o**. Nevertheless, it will be seen that the upper and lower teeth are naturally separated by approximately six millimeters for the vowel *e* = (**i**), whereas they are very close together if not actually in contact for the vowel **o**.

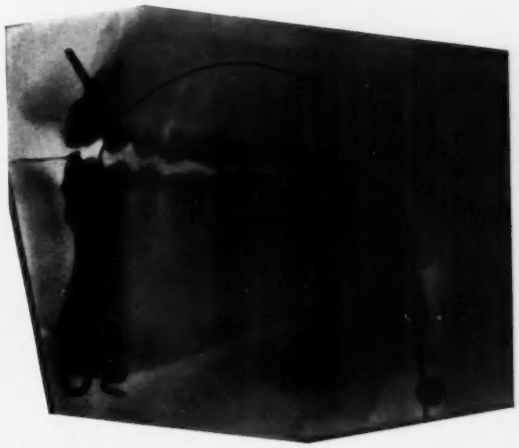

FIG. 5. Normal speech **z** in the **ozo** sentence: "**Oh Zoe** *will be there in plenty of time.*" . . . Note how much smaller the total cavity capacity is than that of Fig. 4 *easy* (**izi**). Yet the latter has a somewhat smaller aperture.

It is of interest to compare these observations with those which might be made concerning **z**, in combination with the two vowels **æ** in the sentence: "*No, they repeated* **as at** *first, the task was not so difficult if you did not think about it too much ahead of time.*" This tongue position is as radically different from either one of the other two as it could possibly be. This will be seen by reference to Fig. 6. The epiglottis is well back against the pharynx and the tube at that point is no larger than a lead pencil in diameter, but it starts to flare immediately above that, as it quite commonly does in the production of an **æ**. There is thus created a typically megaphone-like type of horn in the neighborhood of the upper pharynx. The tongue is fairly flat in the mouth but arches decidedly more toward the hard palate in the forward or buccal part of the mouth than it does for **o**. The blade of the tongue rather than the tip is the part which makes contact just as it did for *e* = (**i**), rather than the tip as it did for **o**. Nevertheless, the separation between the tongue and the juncture of the hard palate is very much greater than it was for *e* = (**i**). It may be further observed that the separation between the tongue and alveolar ridge is over twice as great as it was for the *e* = (**i**) and the teeth in this case are quite close together, as they were for **o** shown in Fig. 5.

It does not seem wise to attempt any complete analysis of all consonants in this paper. But

FIG. 6. Normal **z** in an **æ z æ** position. Sentence: . . . "*They repeated* **as at** *first.*" . . . Observe that: cavity capacity, part of tongue articulating, and tongue position, for all these normal consonants in Figs. 4, 5 and 6 are quite unlike the unnatural prolonged ones in Figs. 1 and 2.

enough has been presented to show that the cavity effect for this one consonant is probably more negligible than we had heretofore assumed. Any really characteristic frequencies which it may have probably might well be sought elsewhere, or at least be considered either adventitious or incidental factors in creating consonant quality differences. The effect of surfaces in splitting the air column or otherwise setting up friction therein and the transients added to the voicing elements by such buzzing and surface frictional effects would seem to be the most basic factors involved in creating most such consonant quality differences.

In conclusion, it might not be amiss to say something in regard to the techniques now being utilized in our laboratories for the study of these consonant effects. Many years ago I announced our first success with motion picture x-rays. Since that time a splendid motion picture x-ray experiment has been announced by my friend, the son of my former teacher Dr. H. Gutzmann in Berlin.

For a long while we sought to make this consonant study by means of such an x-ray motion picture procedure, but that very shortly proved to be inadequate. For the best one can do is to take exposures at the rate of 17 per second, and this becomes a very difficult and dangerous task. Most such x-rays have been taken at the rate of from 3 to 8 per second. In any event, 17 exposures per second are obviously not enough in order to obtain the characteristic tongue positions for these consonants. Since as will be seen from Crandall's study, they vary in length from 2/100 of a second up to not more than 30/100 of a second even in artificial nonsense syllable combinations. And in normal speech, the length of time involved is even much less than this.

In the paper given during this conference in collaboration with Mr. Palomo, I shall consider in more detail the apparatus set-up necessary in order to make our instantaneous exposures of 1/128th of a second which are set off automatically. In this case the contact of the tongue point with the roof of the mouth suffices to release the exposure. When the breath pressure is reduced sufficiently, the x-ray circuit is closed automatically without the operator having to touch any button whatever or otherwise concern himself with the making of the exposure. Since the contact with the roof of the mouth is what releases the exposure, it is obvious that the resulting photograph will be of the tongue position at the point of maximum closure. Synchronization with a sound record and recording needle device shows exactly where the sound occurred in relationship to the total length of the consonant. Consequently a complete check is always had on what was being produced at the moment of exposure. An apology is due for reverting to my old median tongue marker. It is now long since antiquated and modern x-ray rapidity make it a disgrace to use such. Hence no careful experimenter should resort to means of that kind. Nothing whatever should be put in the mouth. For to do so tends to gag the subject, and in any event adds to the possible distortions and non-normal conditions leading to deviation from speech as we know it in our every-day intercourse. But I thought it wise to use it in these first preliminary consonant experiments principally because the amateur radiogopher will be able to follow the same with more degree of assurance. And I did not desire to do any masking or retouching whatever.

Summary

1. Whereas prolonged exposures of more than 1/120 of a second give almost identical tongue positions for the same consonant regardless of the vowels on either side of it (Cf. Figs. 1 and 2 or see Fig. 3) this position is shown to be a distortion.

2. For where the exposure is fast enough and the technique is adequate to catch the consonant as it occurs in rapid normal speech, it is shown to vary with the changing sounds on either side of this **z**.

3. It does not have an invariable and characteristic cavity. The natural period of a supposed cavity capacity postulated by Paget, Crandall, et al., cannot therefore be said to cause its quality differentiation.

4. Nor is its point of contact always the same.

5. Nor is its jaw position.

6. Nor is it always point-lingual.

7. The only apparently significant manifestation which remains fairly constant for this **z** in all combinations is the diameter of the aperture between the tongue and the alveolar ridge.

8. This suggests that the real cause of the quality heard in a **z** is the friction created by an air volume whose pressure at that point is increased by reason of the constricted exit aperture.

9. Perhaps that is the reason why slight variations are manifest even here. For abdominal pressure on the lungs may also be increased to compensate for alveolar aperture differences, or rather the opposite. But in all x-rays here shown the diameters only range from 3 to 4 mm.

10. The horizontal length of that aperture varies more. In some cases being several times as long, ranging approximately from 5 mm to 20 mm.

11. Certainly those variations in aperture diameter cannot be for the purpose of compensating for cavity capacity differences. For the smallest and longest aperture coincides with the largest cavity. Fig. 4.

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An Interpretation of Vibro-Tactile Phenomena

ROBERT H. GAULT,* *Northwestern University*

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OUR organs of hearing and seeing, as well as the animal forms as a whole, are products of an evolutionary development. The zoologists tell us that they have become differentiated from the skin of the body as a whole. Primitive animals had to touch the objects in their neighborhood in order to foster acquaintanceship with them.

This, however, is not a quite accurate picture of the situation for they apparently have a vibratory organ: the beginning of a distance receptor. In higher forms of life it becomes the ear. Particular forms of vibration have become signs of particular objects or events at a distance. But it continues to be a case of touching. We with our normal ears must be in contact with the vibrating air or other medium in order that we may enjoy the experience of audition. This suggests that it may be an arbitrary distinction; saying that *we* hear and that the mollusc and the earthworm do not hear. We both react appropriately to vibratory stimuli. By the same token it may be an arbitrary distinction that we receive vibratory stimuli over an auditory nerve, and therefore hear, whereas certain lower animals receive the same stimuli otherwise and therefore do not hear.

Undoubtedly, in the long line of evolution from lower to higher forms, many variations of structure appear by way of which organisms are enabled to react with increasing niceness to vibratory stimulation.

There is the fish, for example: a vertebrate animal that is measurably free from the necessity of directly touching as a means for becoming acquainted. The fish has something that approximates to the human ear but falls far short of it.

Professor K. v. Frisch and his students at the University of Munich have for long been engaged in illuminating experiments on various representatives of the family of fishes.[1] The lower portion of the ear in *Elritzen* (*Phoxinus laevis*) is the only part of the organ that is concerned specifically with the function of receiving vibratory stimuli. It is the fish's ear *par excellence*. The upper portion—the semicircular canals and ampullae—function only in relation to the maintenance of balance or equilibrium.

When the ear is in normal condition, the animal is capable of detecting a vibratory stimulus when its frequency is as high as 13,000 dv sec. Moreover, they can be trained (by a method that is familiar to psychologists and physiologists) to discriminate frequencies within the range up to 13,000 dv when their difference is one octave. Evidence for such discrimination is found in the fact that when the water in which the fish lives is made to vibrate at the rate, e.g., of 512 dv sec. while it is being fed, there comes a time when the fish behaves as if expecting food when the water vibrates at this rate, even though no food is being offered. At the same time it will not behave in this manner when the water is vibrating at a rate an octave above or below 512 dv. This is objective evidence of discrimination even though the fish does not use our language to tell us that he discriminates.

The next chapter in the story begins with the operative removal of the entire ear leaving only the semicircular canals. In this situation the animal behaves just as before in respect to his responses to vibratory stimulation so long as the range of frequencies employed as stimuli does not exceed 145 dv sec. and he may be trained to make new discriminatory responses.

It is evident enough that at the fish stage in evolutionary development, the ear has not yet taken over all of the hearing function that in earlier stages was much less specialized than it is here, and that was the common labor of a large

* Professor of Psychology.

[1] See, for example, K. v. Frisch, *Die Erforschung des Gehörninses bei Fisches*, Die Wiener Klinische Wochenschrift, No. 20, 1933.

part of the surface or body of pre-fish animals as a whole; a larger and larger part as we retreat from man toward more primitive forms of life.

It has already been pointed out that our own experiments most probably involve, not only the superficially seated sense of touch, but the deeper sense of vibration.[2] This seems to be the plausible explanation for two facts; first, that we are unable to detect a vibratory stimulus when it is applied to the tip of the tongue though this member enables us to make remarkable distinctions among stationary objects through the sense of touch; and secondly, that when vibratory stimuli are applied to the back of the forefinger, where touch spots are relatively few, they can be detected as accurately as when the stimuli are applied to the palmar surface of the same finger where touch spots are much more numerous.

In many places I have published results of a great variety of experiments, all of which together emphasize the fact that among a very great number of patterns of amplified vibration that correspond to forms of speech and music, discriminations can be made with a high degree of success when stimuli are applied only to the finger surface.[3]

All of this raises a fascinating question, the answer to which, I presume, like many another, will depend upon a definition. It was nine years ago when the late distinguished Dr. Victor Vaughn said, in the course of a comment upon the work I am discussing, wrote as follows: "We hear not only with our ears, but with our whole bodies." Are we hearing through our fingers when we make the discriminations to which I have alluded, and others? The only evidence I can obtain that you hear my voice is found in what you do about it.

And so we may legitimately describe the results of our vibro-tactile experiments as evidences of hearing, even though we are assured that the ear is not involved. The human ear, like that of the fish, has not yet taken unto itself all of what may be legitimately called the organism's hearing function.

In our laboratory situation, progress is, in an important measure, a problem of engineering. In other part, it is a product of a richly varied and purposeful experience, in the light of which we draw our inferences from the signs that reach our senses.

I am justified in emphasizing the function of engineering. For men and women of normal native intelligence, once a sufficiently strong motive is supplied, can learn anything that can be brought through the senses into the realm of consciousness. In our situation, the first great problem is to bring our vibrational stimuli to the organs of sense in adequate intensity, regardless of their pitch. That is an engineering problem and when it is solved so that the various forms of vocal language are brought to the finger in the same relations of intensity as the same vibratory patterns normally excite the auditory organ, the finger immediately becomes a better ear than it can possibly be in the absence of instrumental aid.

And this reminds me to say what I can never forget: the work I am representing could not have attained even approximately its present status were it not for the initial engineering aid it has received from Bell Laboratories and more recently from engineers of the Western Electric Company and from Mr. Albert Krause, E.E., of Hamburg, now in Northwestern University.

There is another aspect of our laboratory work to which I must bring attention. The vibro-tactile senses have been, from the beginning of the education of the deaf, employed in connection with the development and improvement of spoken language as well as with its interpretation. We, by aid of our technique, are able to improve upon

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[2] Goodfellow and Ilieva, *The Sensitivity of various Areas to Vibratory Stimuli and its Correlation with the Distribution of Receptors.* (Unpublished.)

[3] For a description of the present form of the Gault-Teletactor through which stimuli are brought to the fingers, see, Goodfellow and Krause, *Apparatus for the Study of Vibratory and Tactual Sensitivity*, Rev. Sci. Methods **V**, 44–46, January (1934). See for a summary of results of experiments: Gault, *A Partial Analysis of the Effects of Tactual-Visual Stimulation by Spoken Language*, J. Frank. Inst. **209**, 437–458, April (1930); ibid., *On the Effect of Simultaneous Tactual-Visual Stimulation in Relation to the Interpretation of Speech*, Ill. Acad. of Sci. **22**, 630–653 (1930); ibid., *On the Identification of Certain Spoken Words by their Tactual Qualities*, J. App. Psychol. **10**, 75–78 (1926); Roberts, *A Two-Dimensional Analysis of the Discrimination of Differences in the Frequency of Vibrations by Means of the Sense of Touch*, J .Frank. Inst. **213**, 283–312, March (1932); Goodfellow, *The Tactual Perception of Musical Intervals*, J. Frank. Inst. **215**, 731–736, June (1933).

previous performance in this regard. This statement finds sufficient support in more than two years of experience in the State School for the Deaf in Jacksonville, Illinois, where the trial continues to go on, in greatly increased scope as compared with its beginning in that institution, under the guidance of Superintendent Daniel T. Cloud[4] and Miss Alice Plouer, who, as teacher, is directly in charge of the work.

Success in this enterprise is due primarily to two factors: in the first place, vocal stimuli, by the means we have developed, are brought to the deaf child's vibro-tactile organs many times more intensely and distinctly than can otherwise be accomplished. And secondly, perhaps equally importantly, because of the enlarged social factor that our technique introduces. For spoken language, both on the side of interpretation and on that of production, is a social invention. Generally speaking, in the conventional school, the individual deaf child is brought alone to the teacher's knee for his lesson in speech. Other members of the class are not in cooperation. In other words, the social circle, for the time being, is narrow. In our situation, on the other hand, there is undoubtedly a strong social motivation, that goes a long way toward guaranteeing that cooperative activity of the whole group will be all the time involved, assuming a competent teacher, such as we have in Jacksonville.

On this point, I am frequently asked how it comes to pass that the kind of stimulation we provide can have the least thing to do with the process of improving speech. I will cite a parallel to the situation I have in mind. Let one of us, who has all his life lived in the north, visit in Alabama during the next twelve months. Such a one will probably return to the north speaking the Alabamish tongue. We need not assume that he deliberately went about it to acquire that form of speech. Though I must say that if the visitor intently goes about making the acquisition, he will thereby increase the probability of a happy issue. It seems that we almost perforce adopt the manner of speech that daily beats upon our ears.

It is an attractive hypothesis that there is a native nerve-muscle mechanism by reason of which our vocal organs are inevitably made ready to produce a given tone the moment the ear is excited by the same tonal stimulus. It is equally probable—perhaps more so—that this inevitability, to whatever extent it obtains, is an effect of conditioning or learning processes. And if so, then in the nature of the case, the same inevitable sequence should be expected when the stimulation is applied, not to a normal ear, but to the vibro-tactile organs.

Finally, I want to say that our experiments afford one more indication among many others that our sensory spheres are not set about by impervious walls. There is probably a "no man's land" between every two; a land that may be taken over, wholly or partly, by one of its adjacent neighbors. I believe this is true at least as between the vibro-tactile and auditory spheres. So that it is difficult or impossible in many instances for either the subject or the other observer to know whether we are confronted with hearing, in the ordinary sense of the word, or with feeling in the ordinary sense of that word. And on my concluding statement there is no possibility for difference of opinion: training of a sensory mechanism has the effect of refining or sharpening it. A well trained deaf or hearing subject, e.g., will detect a vibratory stimulus against his vibro-tactile organs that the untrained —especially the untrained hearing subject—is wholly unable to discover.

Practically, it is of no importance whether this effect comes to pass as a consequence of a change in the sense organ itself or as a result of learning to attend to stimuli that we customarily neglect. All this suggests another meaning of the saying that this particular sensory sphere is not precisely and eternally fixed.

[4] See Cloud, *Some Results from the Use of the Gault-Teletactor*, Am. Annals of the Deaf, May, 1933. Gault, *Drafting the Sense of Touch in the Cause of Better Speech*, Jour. of Expression 1, 126–131, September (1927).

The Effects of Noise upon Human Efficiency[1]

JÛICHI OBATA AND SAKAE MORITA, *Aeronautical Research Institute, Tokyo Imperial University,*
AND
KIN-ICHI HIROSE AND HIROSHI MATSUMOTO, *Psychological Department, Faculty of Letters, Tokyo Imperial University*

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INTRODUCTION

CITY noises and their ill effects are undoubtedly a product of our own age of speed, forming new problems that are attracting the serious attention of scientists as well as administrators in many parts of the world. A great deal of work has already been done in the matter and there is quite an extensive literature dealing with various aspects of the noise problem. The effect of noise upon human efficiency is by all means the most important item concerning the noise, and consequently a considerable number of investigations[2] have also been made with regard to the effect.

Most of the investigations so far made on the effects of noise upon human efficiency, however, rarely went beyond the qualitative stage, merely indicating the existence of the various effects. In our present investigations the experiments were therefore made with a view to obtaining quantitative results on the effects of noise upon human efficiency, with due regard to the nature and intensity of the noise.

Since the noises met with in our daily lives are obviously of such diverse nature that it is almost impossible to study them all, in the present work only a limited number of experiments were made, with the aid of music from gramophone records and pure or meaningless noise. These two kinds of noises[3] were selected because noises affect our efficiency in two different ways; by their loudness and certain characteristics inherent in the noise and also by their particular meaning or rhythm, that is to say, by certain attributes possessed by them of attracting more or less the hearer's attention.

THE EXPERIMENTS

More than ten gramophone records, consisting of jazz, orchestra, instrumental solos, and marching songs were employed. For children of primary schools, records of popular juvenile songs were employed in addition. By means of a gramophone "pickup," vacuum tube amplifier, and a loudspeaker, the sounds emitted by the records were magnified and their intensities were adjusted at will. Thus, in the following experiments, "loud record" means a loudness of from 85 to 90 db, and "weak record" soft sounds of about 35 db.

To produce mere, monotonous noise two methods were resorted to. In the first method, rough concentric grooves were cut with a lathe on the surface of a steel disk of about the size of an ordinary gramophone record, and by using it in place of the record a scratching, irritating noise of about 60 to 65 db was obtained. In the second method, a special noise-machine, consisting of a cylindrical vessel made of thin sheet-metal, in which a number of small pebbles was placed, was rotated by an electric motor at the rate of one or two revolutions per second, and a strong grinding noise of about 85 db produced. Fig. 1 shows this noise machine and Fig. 2 the reproduced oscillograms of these two kinds of noises, both of which are very irregular and complicated. For experiments that lasted several hours, such as the "transcription" experiment, the noise-machine was used, while for all the others the first-named method was employed.

In order to have the illumination of the room in which the experiments were conducted and other conditions constant throughout the investigations and also to minimize the effects of

[1] An investigation carried out with the aid of the subsidy granted the senior author (J. O.) by the Hattori Hôkôkwai.

[2] See Bibliography in D. A. Laird, *The Effects of Noise*, J. Acous. Soc. Am. **1**, 256 (1930).

[3] The word "noise," both here and elsewhere in this paper, is frequently used in a broad sense, including music as well as mere noise.

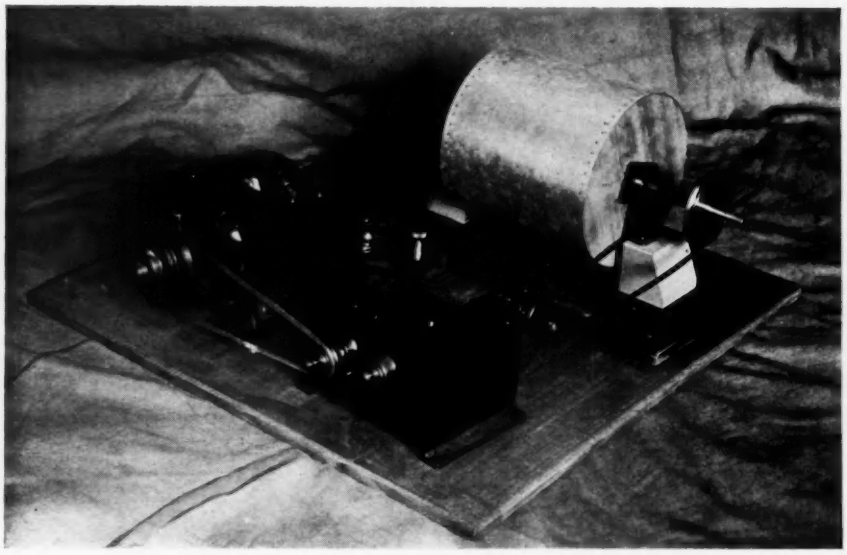

FIG. 1. The noise machine.

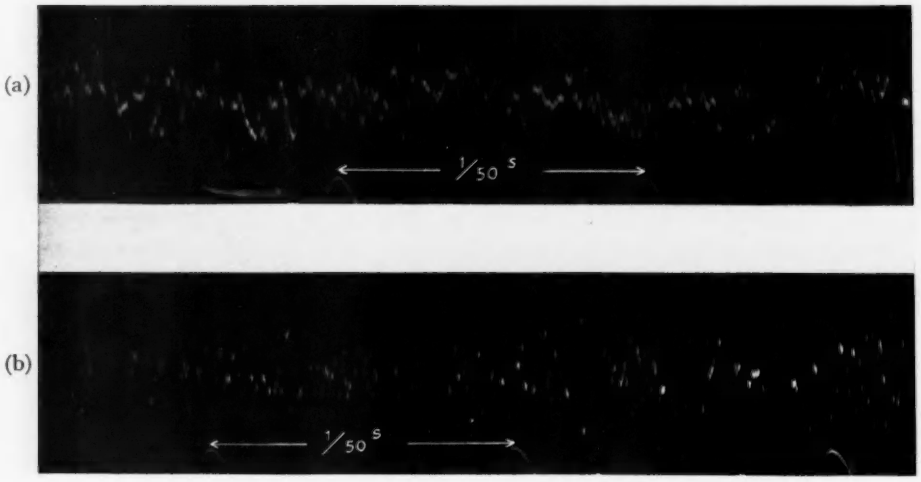

FIG. 2. Noise oscillograms. (a) Steel disk. (b) Noise machine.

extraneous noise, all the experiments with the exception of the last-mentioned one (transcription), were conducted in a room having walls, floor and ceiling covered with sound absorbents. Fig. 3 shows the girls from a primary school engaged under noise conditions on test work allotted them. The last experiment, that of transcription, was conducted in an ordinary office room in order to make the imitation of natural conditions as complete as possible.

For the experiments, the services of eleven boys and thirteen girls, all from a primary school, and of ages ranging from nine to twelve years, were enlisted, besides those of eight adults of more than twenty years of age, most of them assistants in our Institute.

WORK DONE UNDER STRESS OF NOISE

The work given to subjects of the experiment for performance under stress of noise consisted of

FIG. 3.

cancellation, calculation (addition), and transcription.

Fig. 4(a) shows a part of the cancellation sheet and (b) a part of the addition sheet, regarding both of which a short explanation is necessary. In a page of the cancellation sheet are printed 1600 Japanese letters, each letter a syllable, the whole consisting of only eight different letters printed at random without any semblance of system or order. The subject is asked to cancel every one of the two specified letters out of the eight in this confused jumble of 1600 letters, observing the sheet from top to bottom. In the addition sheet are printed 250 sums in single column of four digits each.

The experiments were of the "time-limit" method, in which the amount of work done in the course of a stipulated time interval was measured, and the effects of various noises were determined always by the method of paired comparison. The same work was done in two different conditions, that is, in quiet (silence) and under mere noise, quiet and record, or mere noise and record, and the results were compared.

In order further to safeguard the experiments from being vitiated by results incident to the period during which the subject "warm up" to his work, as well as from the effects of fatigue, the same series of experiments was always repeated in reverse order, and the mean of these two determinations taken as the final result.

For discussing the results, the "accuracy" and the "efficiency" of each individual work were determined as follows:

In the cancellation test,

E : the total number of letters observed by the subject,
c : the total number of letters cancelled correctly,
o : the total number of letters overlooked, hence left uncancelled,
w : the total number of letters cancelled by error.

$$\text{Accuracy} = (c-w)/(c+o),$$
$$\text{Efficiency} = E(c-w)/(c+w).$$

In the addition and transcription tests,

$$\text{Accuracy} = (v-w)/v,$$
$$\text{Efficiency} = v(v-w)/v = v-w,$$

where v is the total amount of work, i.e., the speed, and w the number of errors.

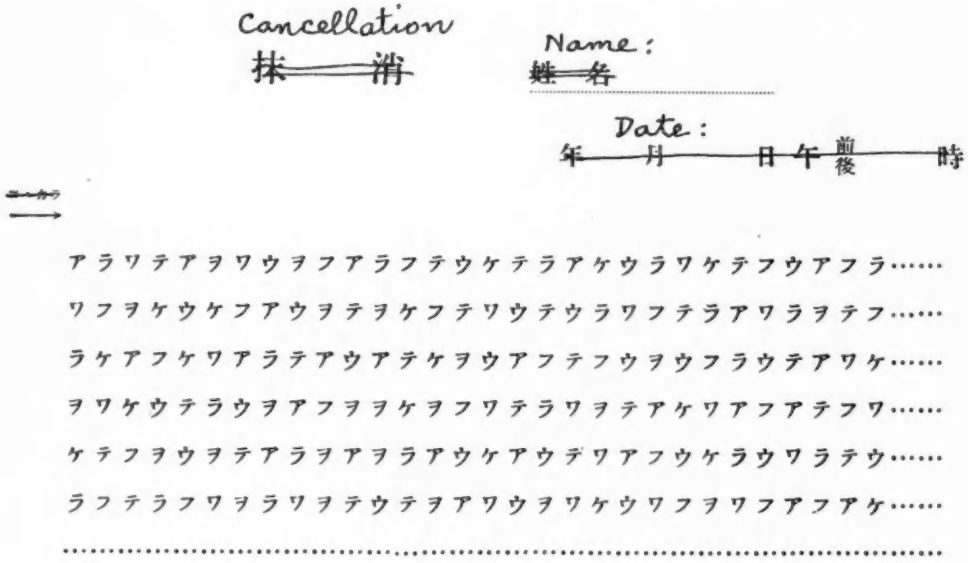

FIG. 4. (a)

Addition

5	7	9	4	9	4	8	9	3	5	7	6	8	5	9	8	7	3
8	8	2	7	6	9	7	7	6	6	2	7	9	8	6	3	9	9
4	5	8	9	8	5	5	2	9	8	3	6	3	6	9	8	7	8
3	9	3	4	7	8	3	7	2	3	9	4	8	4	5	2	5	6
5	6	9	3	3	5	6	9	7	4	7	6	7	8	6	7	5	4
4	9	6	5	9	4	7	5	6	9	8	8	4	6	8	6	8	7
6	2	8	8	6	9	9	3	3	7	4	6	3	5	7	7	9	8
7	4	5	6	9	6	5	9	8	5	7	7	9	8	4	9	8	7
3	4	7	5	9	3	7	4	6	7	8	5	3	4	7	9	8	9
9	9	6	8	2	9	2	7	7	9	3	8	6	9	5	6	7	6
6	7	3	9	8	8	3	9	3	3	8	6	9	5	4	8	5	8
9	5	8	8	3	6	9	4	7	9	2	4	4	8	8	7	3	5

FIG. 4. (b)

It need scarcely be said that had we been able to measure at the same time the physiological factors, such as changes in the respiration, in the pulse, and in the degree of fatigue suffered, the results of the experiments would have been much more interesting, but unfortunately it was not possible to do so.

RESULTS

Experiments A

Table I shows the results of the addition tests that were made with several adult subjects, the time limit being fifteen minutes. In this table, the speed under quiet conditions shows the actual amount of work done, while that under noise denotes the percentage of work done, taking the work accomplished in silence as 100. For example, referring to the work of subject *II*, shown in the first row of the table, this subject made in average 202.5 additions in the course of fifteen minutes, of which 4.5 were wrong, so that the accuracy is 0.978. On the other hand, with noise, his amount of work, that is the speed, as well as the accuracy dropped to 95.1 percent and 99.7 percent, respectively.

It will be seen from this table that the effects differ considerably with the subject, and that the difference appears not only in degree but in sense (plus or minus) as well. For example, in the contrast experiments, quiet and noise, the efficiencies

TABLE I. *Addition test.*

1	Silence			Mere noise		
Subject	Speed	Accuracy	Efficiency	Speed	Accuracy	Efficiency
H	202.5	0.978	198.0	95.1	99.7	94.9
D	311.0	0.995	309.5	96.5	100.3	96.8
M_1	281.0	0.998	280.8	103.9	99.5	103.4
A	206.5	0.990	204.5	101.2	100.6	101.8
Average	250.3	0.990	248.2	99.1	100.0	99.1
2	Silence			Loud record		
H	217.8	0.989	215.3	90.1	100.3	90.4
D	276.5	0.994	275.0	98.7	100.1	98.8
M_1	256.5	0.997	255.8	92.1	100.1	92.2
A	257.3	0.997	256.8	95.4	100.0	95.4
Average	252.0	0.994	250.7	94.0	100.1	94.2
3	Silence			Weak record		
D	358.3	0.999	358.0	96.9	100.0	96.9
A	294.3	0.997	293.5	97.3	100.1	97.4
Average	326.3	0.998	325.8	97.1	100.1	97.1
4	Mere noise			Weak record		
M_1	306.0	0.996	304.7	96.0	99.9	95.9
O	338.0	0.987	333.5	98.7	99.7	98.4
Average	322.0	0.992	319.1	97.3	99.8	97.2

(15-minute mean)

of subjects *H* and *D* diminished, while those of *M* and *A* increased.

Since individual results show such discrepancies, only the average value obtained for a number of subjects will be considered in the following discussion. In order to show the effects clearer, the average results given in the table are shown graphically in Fig. 5. The effects of mere noise, and of the records, both loud and weak, upon the speed and efficiency of adult subjects are very clearly shown by this graph. In the fifteen minutes of calculation, for example, both mere noise and the records reduced the efficiency, the order of effect being noise, weak record, and loud record; that is to say, the loud record had the most effect and noise the least. It will be observed here that the factor which reduces the efficiency is not accuracy but speed, which fact may undoubtedly be attributed to the nature of the work as well as to the greater strain felt by the subject in his efforts to avoid errors from the effect of noise.

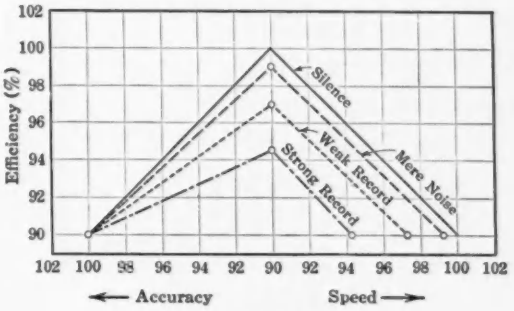

FIG. 5. Addition test.

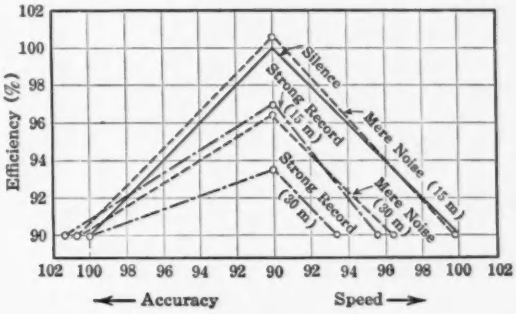

FIG. 6. Cancellation test.

Fig. 6 is a similar graph to the preceding, showing results of the cancellation test with the same adult subjects, the experiments being combinations of quiet and noise, quiet and loud record, and noise and weak record, some lasting fifteen and others thirty minutes. As in the calculation test mentioned above, both record and mere noise showed marked effects, the order being again noise, weak record, loud record.

It is worthy of note that accuracy often gained under noise compared with work performed in silence, indicating that extra efforts were made by the subject to overcome noise. It is also to be noted that the effect always appeared in the speed (total amount of work done) and mere noise hardly affected work that lasted only fifteen minutes. This may perhaps be accounted for by the simple nature of the work (cancellation) compared with calculation.

In short, the following conclusions may be drawn from these two experiments (Experiments A). (1) Although the effects differ considerably with different subjects, yet in general noises diminish the efficiency of the work. (2) Usually, accuracy is not affected, but the working speed is adversely affected. (3) Mere noise hardly affects efficiency, particularly in work of short

duration, whereas record music, even though feeble, had some effect.

Experiments B

The next series of experiments were made with the hope of some light being thrown on the effect of noise on fatigue. For this purpose, the subjects were put on cancellation work, the noise having been introduced in the following manner. For thirty minutes the work was done in silence, after which the noise was introduced for ten minutes, followed by ten minutes of silence and then noise again for another ten minutes. The results are shown graphically in Fig. 7, where the ten-minute averages of the speed, accuracy and efficiency are plotted as ordinates. A glance at this figure will show that upon introduction of mere noise when the subject is more or less fatigued after thirty minutes of continuous work, the effect is quite pronounced, whereas introduction of record music produced little effect. It is interesting to observe also that accuracy was but slightly affected by noise of any kind; in fact it was enhanced in some cases. The speed also suffered very little change with the introduction of music, whether loud or soft, so that the efficiency (speed×accuracy) was somewhat raised. On the contrary, mere noise reduced the speed remarkably, resulting a considerable decrease of efficiency. These results may therefore be taken to mean that, when fatigued, the subject obtains some relief or soothing effect from music, whereas mere monotonous noise enhances the fatigue with consequent adverse effect on efficiency.

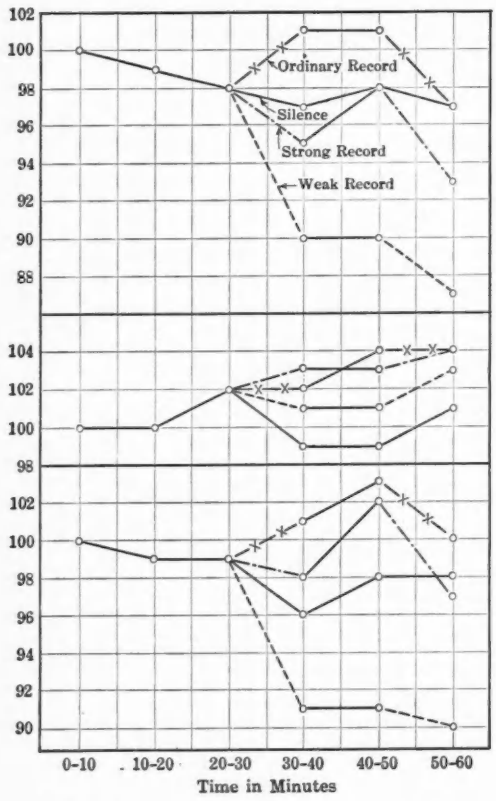

FIG. 7. "Ordinary record" means that the sound was produced by an ordinary gramophone, not by a pickup.

Experiments C

Table II, which gives the average results of experiments made with juveniles, may be regarded as additional illustrations of the results described under Experiments A.

TABLE II.

Sound	Cancellation Speed	Cancellation Efficiency	Addition Speed	Addition Efficiency
Mere noise	86.2	83.3	103	103
Loud record	73.8	67.1	96	96

(15-minute mean)

Experiments D

Owing to the possibility, in all the experiments mentioned above, of the results being affected by the mentality of the subjects through forehand knowledge of the purpose of the tests and of their probable duration, check experiments were made with an adult subject who had been kept quite ignorant of these matters. This subject was made to do transcription work in a regular office for three hours, during one hour of which noise was kept up. The matter for transcription was of a

TABLE III. *Transcription test.*

Sound	Speed	Accuracy	Mistake
Silence	404	0.991	3.8
Mere noise	394	0.924	29.3
Silence	398	0.990	4.0
Weak record	389	0.982	7.5
Silence	411	0.995	6.1
Loud record	423	0.971	12.7
Mere noise	358	0.991	3.4
Weak record	387	0.973	9.9

(15-minute mean)

nature scarcely to attract the interest of the worker. The results are shown in Table III.

Although it would be rash to draw definite conclusions from an experiment with one solitary subject, the following conclusions may be drawn. Contrary to the experiments so far described, the effect of the noise appeared in the accuracy instead of in the speed, the introduction of noise resulting in an increase of errors. In the contrast experiments, quiet and loud record, mere noise and weak record, the introduction of music always resulted in increased speed, which fact seems to be the similar effect as in the Experiments B, that is to say, the effect of music was soothing and refreshing to the fatigued subject. In the present case, the work having been continued for a long period over one hour, the effect appeared much more remarkably than in the previous cases.

Summary and Conclusions

The data suggest the following tentative conclusions.

There is no doubt that the noise, mere noise as well as music, affects human efficiency. The factor on which the effect appears differs, however, according to the individual with whom the test is made and to the nature of the work he is doing. As to the nature of the noise, record music, even when softly played, affects the work much more than mere noise, a fact that explains why, in modern cities, powerful radio music sometimes evokes complaints from neighbors on the score of interference with work or study, and also from sick people. Mere noise, which has but little undesirable effect when of short duration, produces marked effects upon a fatigued worker. Music, on the other hand, has a soothing effect upon tired and jaded nerves.

Acoustical Society News

The spring meeting of the Society will be held April 30–May 1 in New York City. Mr. H. A. Frederick, Bell Laboratories, 463 West Street, New York City, has charge of the program and arrangements. The second meeting of the Society in 1934 will be a joint session with the American Physical Society and the A.A.A.S. in Pittsburgh during the Christmas holidays.

Attention of members is called to a series of articles on acoustics which is appearing in the Physics Forum section of *The Review of Scientific Instruments*. Thus far the following papers have been published: *A Survey of Modern Acoustics*, by F. R. Watson in the May issue, 1933; *Noise*, by E. E. Free, July, 1933; *The Absorption of Sound*, by V. O. Knudsen, December, 1933. Other papers planned for later issues are as follows: *Recording and Reproducing Sound*, by H. A. FREDERICK, in the May issue, 1934; *The Broadcasting of Music*, by J. P. MAXFIELD, in the July issue, 1934.

Books Received for Review

The Voice. Its Production and Reproduction. DOUGLAS STANLEY AND J. P. MAXFIELD, published by Pittman and Company, New York, 1933, 287 pages, cost $2.50. This book sets forth the results of an ambitious and commendable cooperation between a musician and scientist to advance the training of the voice. A review of the book appeared in the November, 1933, issue of *The Review of Scientific Instruments*, page 631, by C. E. SEASHORE.

Practical Acoustics for the Constructor. C. W. GLOVER, published by Chapman and Hall, London, 1933, 468 pages, cost 25 shillings. A review of this book will appear in the July, *Journal of the Acoustical Society*.

College Physics. A. L. FOLEY, published by Blakiston, Philadelphia, 1933, 759 pages, cost $3.75. Professor Foley's interest in acoustics has led him to include five chapters of interesting discussions and problems in sound.

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